# FINAL REPORT

## Advanced Lighting Controls for Reducing Energy Use and Cost in DoD Installations

## ESTCP Project EW-201012

MARCH 2013


Maulin Patel
Satyen Mukherjee
Eric Shen
**Philips Research N. A.**

Sree Venkit
Matt Helm
**Philips Lighting Electronics N. A.**

Francis Rubinstein
Abby Enscoe
**Lawrence Berkeley National Laboratory**


*This document has been cleared for public release*

# REPORT DOCUMENTATION PAGE

*Form Approved OMB No. 0704-0188*



| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| March 22, 2013 | Draft Final Report | From April 2010 to Nov 2012 |

**4. TITLE AND SUBTITLE**
Advanced Lighting Controls for Reducing Energy Use and Cost in DoD Installations

**5a. CONTRACT NUMBER**
W912HQ-10-C-0034

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Patel Maulin, Mukherjee Satyen,
Rubinstein Francis, Enscoe Abby,
Venkit Sree, Helm Matt,
Shen Eric

**5d. PROJECT NUMBER**
EW-201012

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Philips Research North America
345 Scarborough Rd, Briarcliff Manor, NY
Philips Lighting Systems & Controls
10275 W. Higgins Rd. Rosemont IL

Lawrence Berkeley National Laboratory
1 Cyclotron Rd, Berkeley, CA

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Environmental Security Technology

4800 Mark Center Drive
Suite 17D08
Alexandria, VA

**10. SPONSOR/MONITOR'S ACRONYM(S)**
ESTCP

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION / AVAILABILITY STATEMENT**
Distribute only as approved by the SERDP/ESTCP Program Office, release unlimited

**13. SUPPLEMENTARY NOTES**
VIEWS, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE THOSE OF THE AUTHOR(S) AND SHOULD NOT BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF DEFENSE POSITION OR DECISION UNLESS SO DESIGNATED BY OTHER OFFICIAL DOCUMENTATION.

**14. ABSTRACT**
Energy consumption in DoD installations consisting of 2.2 billion sq. ft. of building space is a major concern due to cost of energy, nearly $4 billion annually, as well as resulting carbon emission. Lighting is one of the most pervasive energy consuming elements present in these installations and also impacts the load of HVAC systems due to heat generation. Therefore reducing lighting related energy consumption by means of advanced lighting control strategies including occupancy sensing, light tuning, daylight harvesting and proper lighting design is an effective way to increasing the energy efficiency of the installations. To demonstrate this and quantify the energy savings possible with advanced lighting controls system, Philips in partnership with Lawrence Berkeley National Laboratories has carried out a demonstration project deploying three lighting control system solutions in three chosen buildings in Fort Irwin, California over a period of nearly two years. The results have shown 43-78% lighting energy savings relative to a 1989 Code Baseline and as much as 15% savings in HVAC loads due to advanced lighting controls. This report describes the details of this project and the results obtained.

**15. SUBJECT TERMS**
Integrated lighting controls, occupancy sensing, daylight harvesting, personalized dimming, motorized automated shading control, visual comfort, glare mitigation, Dynalite, OccuSwitch

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| | | | | | Satyen Mukherjee |
| a. REPORT | b. ABSTRACT | c. THIS PAGE | UU | 180 | 19b. TELEPHONE NUMBER *(include area code)* |
| U | U | U | | | 914-945-6320 |

**Standard Form 298 (Rev. 8-98)**
**Prescribed by ANSI Std. Z39.18**

# Table of Contents

## Lists of Figures

## Lists of Tables

## List of Acronyms

| *Acronym* | Definitions |
|---|---|
| *AC* | *Alternate Current* |
| *ANSI* | *American National Standards Institute* |
| *ANOVA* | *ANalysis Of Variance* |
| *ASHRAE* | *American Society of Heating, Refrigerating, and Air-Conditioning Engineers* |
| *BCVTB* | *Building Controls Virtual Test Bed* |
| *BkWh* | *Billion kiloWatt hours* |
| *BLCC5* | *Building Life-Cycle Cost Program* |
| *BMS* | *Building Management System* |
| *CoN* | *Certificate of Networthiness* |
| *CP* | *Control Panel* |
| *C&P* | *Cost and Performance* |
| *COP* | *Coefficient of Performance* |
| *COTS* | *Commercial Off-The-Shelf* |
| *CRI* | *Color Rendering Index* |
| *CT* | *Current Transducer* |
| *DALI* | *Digital Addressable Lighting Interface* |
| *DC* | *Direct Current* |
| *DDE* | *Dynamic Data Exchange* |
| *DDP* | *Draft Demonstration Plan* |
| *DHCP* | *Domain Host Configuration Protocol* |
| *DIACAP* | *DoD Information Assurance Certification and Accreditation Process* |
| *DoD* | *Department of Defense* |
| *DoE* | *Department of Energy* |
| *DPW* | *Directorate of Public Works* |
| *FCC* | *Federal Communications Commission* |
| *ECIP* | *Energy Conservation Investment Program* |
| *EMI* | *Electromagnetic Interference* |
| *EPA* | *Environmental Protection Agency* |
| *ESTCP* | *Environmental Security Technology Certification Program* |
| *EUI* | *Energy Use Intensity* |
| *FDP* | *Final Demonstration Plan* |
| *FEMP* | *Federal Energy Management Program* |
| *GHG* | *Green House Gases* |
| *GUI* | *Graphical User Interface* |
| *GS* | *General Schedule* |
| *GSA* | *General Services Administration* |
| *HVAC* | *Heating, Ventilation and Air Conditioning* |
| *HQ* | *Head Quarter* |
| *IESNA* | *Illuminating Engineering Society of North America* |
| *ILDC* | *Integrated Lighting and Daylight Control* |

| | |
|---|---|
| *IT* | *Information Technology* |
| *IP* | *Internet Protocol* |
| *ISM* | *Industrial, Scientific and Medical* |
| *LAN* | *Local Area Network* |
| *LBNL* | *Lawrence Berkeley National Laboratory* |
| *LCCA* | *Life-Cycle Cost Analysis* |
| *LED* | *Light Emitting Diode* |
| *LPD* | *Lighting Power Density* |
| *MAC* | *Medium Access Control* |
| *MCF* | *Mil Cubic Feet* |
| *MILCON* | *Military Construction* |
| *MMT* | *Million Metric Tons* |
| *NIST* | *National Institute of Standards and Technologies* |
| *OLED* | *Organic Light Emitting Diode* |
| *PC* | *Personal Computer* |
| *PENAC* | *Philips Electronics North America Corporation* |
| *PI* | *Principal Investigator* |
| *PLE* | *Philips Lighting Electronics* |
| *PMT* | *Program Management Team* |
| *PNLCS* | *Philips Networked Lighting Control System* |
| *PRNA* | *Philips Research North America* |
| *R&D* | *Research and Development* |
| *ROI* | *Return on Investment* |
| *RF* | *Radio Frequency* |
| *RFQ* | *Request for Quotation* |
| *RMS* | *Root Mean Square* |
| *SCE* | *Southern California Edison* |
| *SEMS* | *SERDP and ESTCP Management System* |
| *SIOH* | *Supervision, Inspection and OverHeads* |
| *SIR* | *Savings/Investment Ratio* |
| *TCP* | *Transmission Control Protocol* |
| *TOU* | *Time Of Use* |
| *UPS* | *Uninterruptible Power Supply* |
| *US* | *United States* |
| *VPN* | *Virtual Private Network* |
| *ZC* | *Zone Controller* |
| | |

## Acknowledgements

Authors would like to acknowledge the gracious support of Muhammad Bari, Frank Demarest, Sgt. Robinson, SSG. Christina Ross, Bill Anderson, Justine Dishart, Mary Hastings, Gary Cooper and other DPW staff at Ft. Irwin, CA. Authors are also grateful to Osvaldo Velarde, John Dean, Gene Turkenich, Dagnachew Birru, Jeremy Drysdale, Bill Friday, Yao-Jung Wen, Butch Huvaere, Murali Mani and Vladimir Bazjanac for their contributions.

This material is based upon work supported by the U.S. Army Corps of Engineers, Humphreys Engineer Center Support Activity under Contract No. W912HQ-10-C-0034.

## Executive Summary


Background and Intent:
The massive footprint of mostly old building stock in the Department of Defense's (DoD) inventory offers significant opportunities for reducing energy consumption, carbon emissions and operating costs. Buildings and facilities account for about 70% electrical energy consumed by the DoD. Lighting is a significant component of this. Existing lighting systems in many DoD facilities consume excessive electrical energy because they are often outdated, inefficient and lack automated controls. In many unused areas lights are inadvertently left on, wasting energy. Spaces are often overlit or underlit, and occupants have little control over their lighting environment leading to visual discomfort and dissatisfaction. In addition, natural light is typically not utilized for energy savings. All of these factors result in increased energy consumption, higher operational and maintenance costs, increased lifecycle costs, and reduced workforce productivity. Therefore, the intent of this project is to retrofit buildings with advanced lighting control systems that combine dimmable light sources, occupancy and daylight sensors and intelligent controls to significantly lower the lighting energy consumption as well as reduce cooling loads due to the thermal effects of lighting. Furthermore, appropriate control and monitoring systems can, lower overall maintenance cost and improve occupant satisfaction. These savings with lighting control systems can take the DoD a long way towards meeting its energy conservation obligations set forth by regulations, executive orders and directives.

Lighting Control Systems Deployed:

The DoD's Environmental Security Technology Certification Program (ESTCP) commissioned a team consisting of Philips and LBNL to study the performance of advanced lighting control systems in DoD buildings. Philips developed and deployed the lighting control systems and LBNL carried out the evaluation of energy savings and occupant surveys by collecting pre and post retrofit data and performing all the data analysis. In this report we present the cost and performance analysis of three lighting control systems deployed in three buildings in Ft. Irwin, CA described below.

I. **OccuSwitch Wireless** is a room-based lighting control system employing dimmable light sources, occupancy and daylight sensors, wireless interconnection and modular control to provide energy savings through occupancy sensing, dimming and daylight harvesting.

II. **Dynalite** is a distributed control-based, wired networked building-wide lighting control system offering scene settings, personalized dimming, scheduling, occupancy sensing and daylight harvesting to provide energy savings as well as convenient ambience for different activities.

III. **Hybrid ILDC** (Integrated Lighting and Daylight Control) is a combination of wireless and wired control solution for building wide networked system that maximizes the use of daylight while improving visual comfort through an integrated control of electric lights and motorized blinds. It implements a variety of control strategies including occupancy sensing, personalized dimming and glare avoidance.

Performance Results:

The goal of this project was to study the energy, environmental, economic and user benefits of the above three lighting control systems in DoD buildings. Both quantitative and qualitative performance objectives were defined to capture the benefits of the systems.

Table 1 briefly summarizes the performance of the three systems against the objectives and success criteria agreed with ESTCP. As can be seen from the table, most of the objectives were met during the demonstration with exception of two which are discussed below. For detailed analysis of results please see performance assessment section 6.

Table 1: Performance results

| Performance Objective | Success Criteria | Results | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Hybrid ILDC | | | OccuSwitch | | | Dynalite | | |
| Reduce electrical energy consumption for lighting | >45% reduction in EUI compared with code baseline lighting energy | 79% | | | 62% | | | 43% | | |
| | | Y | | | Y | | | Y in 80% of space | | |
| Reduce lighting demand by better lighting design | >25% reduction in Peak LPD compared with code baseline LPD | 60% | | | 47% | | | 52% | | |
| | | Y | | | Y | | | Y | | |
| Reduce Carbon footprint of the lighting system | >45% reduction in carbon footprint compared to a building with code baseline lighting energy in the same region | 79% | | | 62% | | | 43% | | |
| | | Y | | | Y | | | Y in 80% space | | |
| Cost-Effectiveness | Building size | Sm | Md | Lg | Sm | Md | Lg | Sm | Md | Lg |
| | >2 SIR over a 20 year period | 1.6 | 2.8 | 3.4 | 1.8 | 2.8 | 4.4 | 1.2 | 1.6 | 2.4 |
| | | N | Y | Y | N | Y | Y | N | N | Y |
| | <7 years Payback | 6.25 | 3.89 | 3.09 | 5.37 | 3.56 | 2.28 | 8.67 | 6.47 | 4.29 |
| | | Y | Y | Y | Y | Y | Y | N | Y | Y |

As shown in Table 1, the three systems performed differently with respect to energy savings as expressed in EUI/carbon footprint reduction, peak lighting power density and cost effectiveness. This is partly due to the differences in the characteristics of the buildings they were deployed in and partly due the energy savings features of the systems. For instance the size of the buildings is an important parameter that determines the system cost per unit area as fixed hardware cost, such as servers and controllers are amortized over the entire area. To provide a more generalized picture that can be applied across the entire DoD facilities, three different building size scenarios have been considered – small, medium and large defined specifically in section 7.5. With this classification, it is seen that payback <7 years is met in most cases with the exception of the small area category for the Dynalite system. Savings to investment ratio objective (>2) is met in

the large buildings for all three systems and medium buildings for Hybrid ILDC and OccuSwitch systems. In small buildings the SIR objective is not met.

With respect to system reliability, system maintainability, work plane illuminance and ease of installation and commissioning all three systems met the objectives with significant margin. This is a testimony to the robustness of the systems in general and are independent of building characteristics.

Systems integration performance, or the effect of the lighting control systems on the HVAC load, as computed from Energy Plus model based simulations are consistent with expectations and met the project objectives. It should be pointed out that, the actual energy savings performance of the HVAC systems will be dependent on the type and effectiveness of the HVAC systems deployed in the buildings.

While on the average for the three systems taken together the performance well exceeded the key targets (energy cost and carbon footprint), the Hybrid ILDC and OccuSwitch systems met or exceeded the key performance objectives and the Dynalite achieved 43% reduction in EUI compared with code baseline lighting energy against the target of at least 45% reduction in EUI, marginally falling short of the target.

Overall this demonstration project has shown that advanced lighting control systems deployed in existing DoD buildings can provide significant energy cost and carbon footprint reduction ranging from 43% to 79% depending on the building geometry, legacy system deployed and usage pattern. The three systems varied in terms of features and performance, each one being optimal for a certain class of building types. For large buildings (over 100,000 sq.ft.) networked systems such as the Dynalite or Hybrid ILDC are expected to provide the best results whereas for medium to small sized buildings standalone room based systems such as the OccuSwitch Wireless system would be more appropriate.

Economic factors such as payback and SIR are strongly dependent on building or deployment size due to economy of scale and amortization of control hardware over the total building. From DoD's perspective, since energy and economic benefits are the primary driving factors, it is also important to consider life cycle cost (LCC) savings. Given the goal of DoD to reduce energy consumption by 30 % by 2015 over a 2003 baseline, lighting controls systems demonstrated in this project, if deployed DoD wide, can result in 11-20% overall energy savings for DOD.

Following the encouraging results of this demonstration project, the Dynalite and the Occuswitch wireless systems were introduced as commercial products in the US market in 2010 and 2012 respectively.

# 1 INTRODUCTION

According to the Energy Information Administration, lighting accounted for 37.6% of site electricity used in US commercial buildings[1]. Advanced lighting controls offer one of the most cost-effective means to reduce the energy, carbon footprint, and operating costs of existing buildings. Lighting controls regulate the timing and intensity of light in order to provide the right amount of light when and where it is needed in a cost-effective way. In addition to saving energy, advanced controls can improve occupant satisfaction by providing personal control over light conditions.

## 1.1 BACKGROUND

Lighting is one of the largest energy-consuming elements in most buildings at DoD installations including barracks, administrative buildings, residential buildings, recreation areas, maintenance shops, schools, medical facilities, etc. In large military installations such as Fort Hood in Texas, lighting represents around 28% and cooling represents 33% of the total electrical energy used [2].

Existing lighting systems at many DoD facilities tend to be older, unmetered, outdated and equipped with only manual switches at the room or area level. Common lighting energy waste is seen, for instance, when lights are inadvertently left on in daylit or unoccupied areas. This not only contributes to wasted lighting energy but also increases the cooling load on air-conditioning systems, thereby compounding energy waste in buildings.

Lighting controls can have a large impact on these areas by reducing wasted lighting energy, reducing cooling loads due to the thermal effects of lighting, and improving occupant satisfaction and productivity. This can be accomplished by detecting occupancy, harvesting daylight, and exploiting integrated control strategies while enhancing user productivity and comfort. Furthermore, emerging communications technologies, particularly wireless, will reduce the cost of installing advanced lighting controls into older buildings typical of DoD inventory.

Different building types (barracks, administrative buildings, maintenance shops, etc.) require different lighting conditions at different times for optimum occupant productivity and comfort. The selection of the best lighting control solution depends upon a number of factors such as building type, location, climate zone and usage profiles. Therefore, the project team deployed and demonstrate three complementary lighting control systems that together meet different DoD facility requirements.

The advanced lighting control systems deployed are: Hybrid ILDC (Integrated Lighting and Daylight Control), OccuSwitch Wireless and Dynalite. These systems offer unique cost-benefit advantages.

Hybrid ILDC is a building-wide networked system that maximizes the use of daylight while improving user comfort through integrated control of electric lights and motorized blinds. The system features wireless connectivity among sensors and actuators within a zone and exploits wired connectivity across zones to enable building-wide deployment and monitoring.

OccuSwitch Wireless is a room-based lighting control system which reaps energy savings through occupancy sensing, dimming and daylight integration.

Dynalite is a building-wide wired lighting control system offering scene settings, personalized dimming, scheduling, occupancy sensing, daylight harvesting, distributed control and interfaces with existing building management systems including HVAC.

While all three systems are designed to optimize lighting related energy consumption resulting in considerable energy savings, the Hybrid ILDC system, with its innovative integrated control, also reduces HVAC cooling load, thereby allowing additional energy savings. The exact amount of energy savings will depend on building type, climate conditions and usage pattern. For wide scale adoption of advanced lighting control systems, energy conservation alone is not sufficient; cost-effectiveness, ease of installation and user satisfaction are equally important.

## 1.2 OBJECTIVES OF THE DEMONSTRATION

The principal objective of this project is to quantify the energy, environmental, economic and user benefits of deploying advanced lighting control technologies at a representative U.S. Army installation (Fort Irwin). In order to accomplish this goal, key lighting control strategies including scheduling, personalized dimming, daylight harvesting, occupancy sensing and scene setting were implemented.

The offered system solutions were specifically tailored to suit the unique characteristics and operating conditions of the respective target facility. The engineering trade-offs to achieve desirable balance among facility characteristics, cost of implementation and operation, user comfort, compatibility with other building management systems were evaluated. Technical challenges relating to robustness of the system and installation complexity affecting optimal cost/benefit trade-off of the featured solutions were addressed. The performance of each technology was evaluated in a variety of usage scenarios to judge the efficacy of each system. To verify the performance in DoD settings, empirical evidence to evaluate energy savings, demand savings, cost-effectiveness, payback time, system reliability, system maintainability, ease of installation and user satisfaction as a result of deploying these systems were gathered. Furthermore, using model-based simulations, the impact of the demonstrated lighting system on HVAC energy was quantified. Results of the performance analysis are discussed in Section 6.

## 1.3 REGULATORY DRIVERS

The Department of Defense (DoD) operates about 307,295 buildings spanning over 2.2 billion square feet of space. It spends about $3.784 Billion on facilities energy. This enormous footprint offers large opportunities for energy and cost savings. To exploit those opportunities, a number of legislations, executive orders and DoD directives have been issued which mandate significant energy efficiency improvements. The most significant ones for the DoD and other federal buildings are as follows:

- The Energy Policy Act of 2005
- Federal leadership in High Performance and Sustainable Buildings. memorandum of Understanding of 2006

- Executive Order 13423: Strengthening Federal Environmental, Energy, and Transportation Management of 2007
- The Energy Independence and Security Act of 2007
- Army Energy Security Implementation Strategy of 2009
- Executive Order 13514-Federal Leadership in Environmental, Energy and Economic Performance of 2009
- Unified Facilities Criteria(UFC) 3-400-01 Energy Conservation, 2008
- Department of Defense Energy Manager's Handbook, 2005

Furthermore, activities to be undertaken under this project are complementary with other efforts in the public sector. Department of Energy's (DoE's) Building Technologies Office invests about $100 million annually on improving building energy efficiency through a broad portfolio of programs. The DoE's Commercial Building Program includes National Market Outreach and Engagement, Commercial Building Energy Alliances and National Accounts. These are strategic alliances between DoE, private businesses and organizations created to achieve strong market demand for buildings with exemplary energy performance.

The energy conserving methods demonstrated in this report are aligned with the U.S. DoE's Federal Energy Management Program (FEMP) Procurement Challenge, which incentivizes Federal Energy Managers to comply with Executive Orders. In particular, these advanced lighting technologies will go a long way towards helping Federal Buildings, of which DoD's share is 66%, comply with Executive Orders 13423 that mandates 30% energy reduction in federal buildings by 2015 when compared to a 2003 baseline.

# 2 TECHNOLOGY DESCRIPTION

DoD facilities have diverse lighting needs and constraints, given variations in building characteristics, use patterns, occupancy profiles, budgets and operational considerations. No single lighting control solution can optimally satisfy these diverse needs. Therefore, this project deployed and demonstrated three different lighting control systems that satisfy DoD facility requirements especially with regards to cost-effectiveness in a range of operating conditions.

The three systems to be deployed are:

I. **Hybrid ILDC** (Integrated Lighting and Daylight Control) is a system that maximizes the use of daylight while improving user comfort through integrated control of electric lights and motorized blinds. The system features wireless connectivity among sensors and actuators within a zone and exploits wired connectivity across zones (thus "hybrid") to enable building-wide deployment.

II. **OccuSwitch Wireless** is a room-based lighting control system which reaps energy savings through occupancy sensing, dimming and daylight integration.

III. **Dynalite** is a distributed control based building-wide lighting control system offering scene settings, personalized dimming, scheduling, occupancy sensing and daylight harvesting.

## 2.1 TECHNOLOGY OVERVIEW

The functionality, architecture and operation of each system are described below.

### 2.1.1 Hybrid ILDC

***Functionality:*** Electric lighting control and daylight (blinds or shades) control are both essential for regulating interior lighting conditions. It is critical for both systems to complement each other to create a comfortable and productive visual environment with maximum energy efficiency.

Existing lighting control and shading systems typically operate independently, thereby leading to sub-optimal energy efficiency and sometimes causing inconvenience to users. The Hybrid ILDC system implements innovative integrated control algorithms which integrate artificial light with daylight control, thereby fully optimizing energy savings while enhancing user comfort.

The system combines user preferences with sensor readings (occupancy and light level) to harvest natural light through integrated control of motorized blinds and electric light. Additionally, integrated control reduces HVAC loads by optimizing solar gain and the thermal effects of electric lighting.

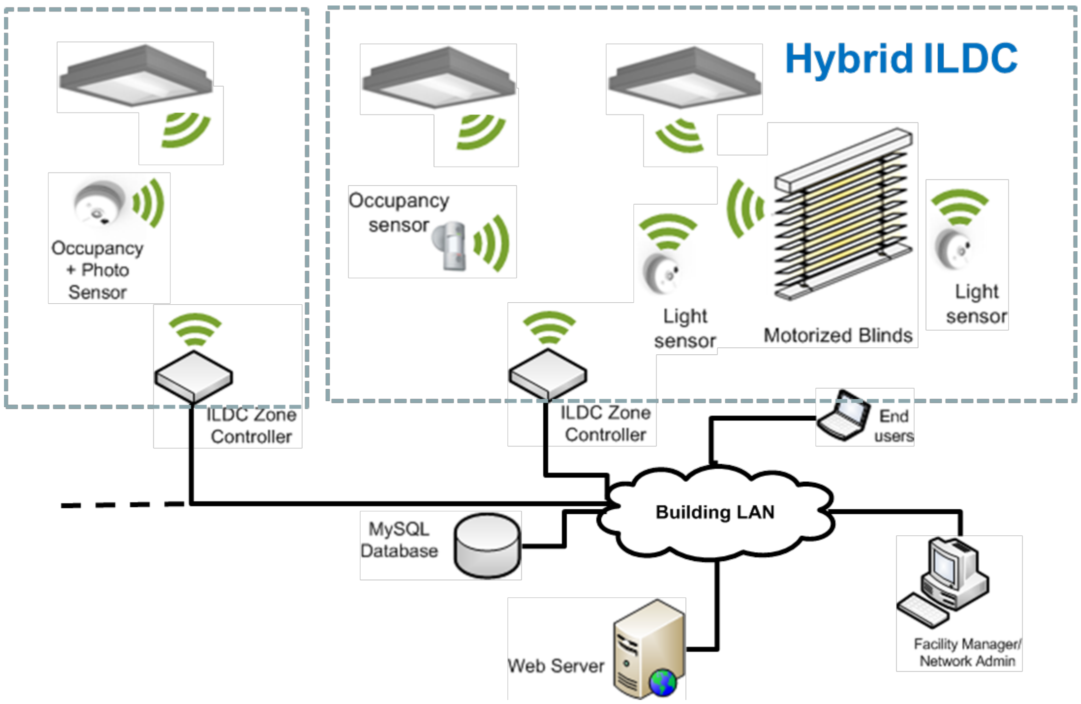



Figure 1: System architecture of Hybrid ILDC

***Architecture:*** As shown in Figure 1, the building area is divided into non-overlapping zones, each associated with a Zone Controller (ZC) that controls daylight and artificial light in a closed-loop integrated fashion. The ZC is wirelessly connected to dimming ballasts, motorized blinds, and sensors within its zone using the ZigBee PRO standard [3]. Wireless connectivity works well in retrofit applications because it eliminates the need for additional control wiring, which is expensive to install in existing ceiling systems. Having wireless occupancy sensors and photosensors is a definite advantage because the sensors can be strategically located given the office layout and occupancy conditions. As space needs change, wireless sensors can be easily re-located to their optimal locations.

The ZC monitors the state of devices, centralizes the collection, processing, and storage of control data, and implementing the specific palette of control strategies. In addition to the ZigBee interface, the ZC has an interface to a building-wide network (e.g. Ethernet LAN), which allows for remote communication with a Database, a desktop GUI, and a Web Server, as depicted in Figure 1. The system features wireless connectivity among sensors and actuators within a zone and exploits wired connectivity across zones (thus "hybrid") to enable building-wide deployment. The combination of wireless and wired connectivity is an important aspect that makes the architecture more scalable. Furthermore, IP connectivity can leverage existing IT infrastructure for easy retrofit.

Each user's workstation is associated with corresponding sensors, window blinds and fixtures to enable personalized integrated control. Examples of user preferences include illuminance setpoints, glare trigger setpoints, light levels, blind heights, and slat tilt angles. Users can input preferences and control the system through a web interface or a desktop GUI application that

provides manual and automatic control options. Occupants can also override the control system to turn the lights off with standard wall switches.

The web system includes facility manager and network administrator specific web interfaces for supervisory and administrative controls. End users can only control their associated devices, such as task lights and blinds in a private office, whereas facility managers have special privileges to control multiple zones. The network administrator can manage networking and system configuration.

***Operation:*** Zone controllers combine sensor readings with user preferences to derive the optimal electric light levels and blind positions. The schematics of the ILDC control strategy are illustrated in Figure 2. The goal of an integrated control strategy is to maintain task illuminance close to the desired set point in the occupied state while capitalizing on daylight and minimizing electric light utilization. To improve the system's stability and avoid rapid fluctuations, the system maintains illuminance levels within a set point defined as a range rather than a specific value.

If the space is unoccupied, the lights are turned off. A window-mounted, exterior-facing glare control photosensor measures the vertical illuminance incident on the window, detecting glare when this exceeds a certain threshold. The system detects interior illuminance using ceiling mounted photosensors which are calibrated during commissioning to estimate workplane illuminance. If the space is occupied, the blinds are opened to allow in daylight to an extent that does not cause discomfort (glare), while the lights are dimmed so that the overall illumination meets the user's requirements. The illuminance is periodically compared with a reference set point to adjust lights and blinds.

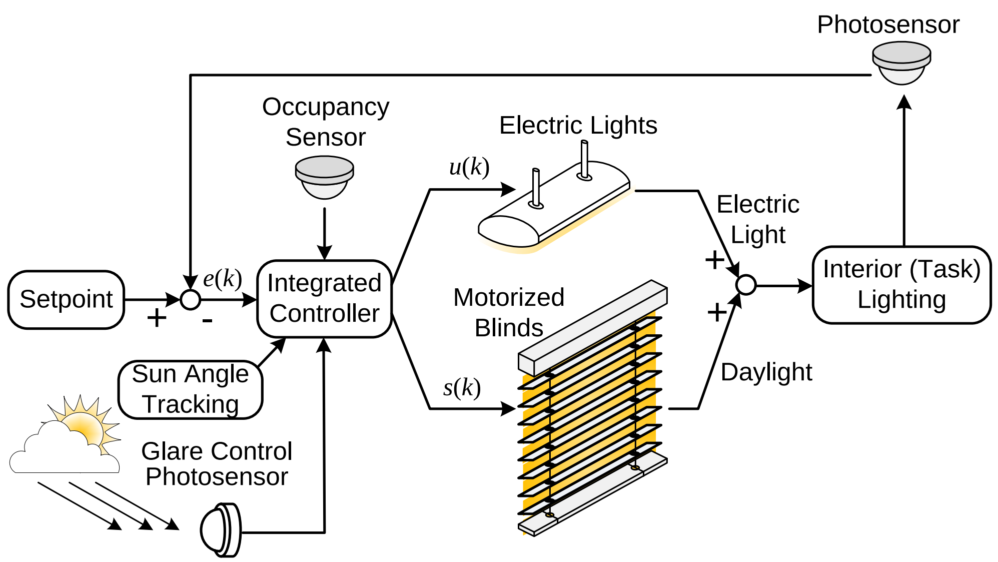



Figure 2: Schematics of the Hybrid ILDC system

When the interior light sensor detects insufficient light to reach the target set point and blind slats are partially open, the controller attempts to open the blind slats incrementally to admit more daylight while ensuring that slat angle stays within the permissible range decided by the glare

control strategy. If the set point cannot be met even after the blinds slats are open to the maximum extent possible, the electric lights are incrementally brightened to compensate for insufficient daylight. Similarly, when the interior light sensor illuminance is above the set point level, the electric lights are slowly dimmed, and if the set point is not reached even after the lights are turned off, the blind slats are closed incrementally to reduce daylight admission until the illuminance meets the target.

Hybrid ILDC supports blind slat angle control based on HVAC mode to optimize energy in an unoccupied state. However, this feature was not enabled at Fort Irwin due to lack of integration with the HVAC system.

Please note that the Hybrid ILDC system is an advanced research prototype. Hence, there are some characteristics and features that do not reflect product-grade system performance.

#### 2.1.2 OccuSwitch Wireless

***Functionality:*** OccuSwitch Wireless is a room-based lighting control system that uses a wireless multi-sensor to measure occupancy and light levels within the room and transmits that information to a wall-mounted dimmer switch that can switch ON and OFF the room lighting as well as dim it to an appropriate level. The OccuSwitch dimmer controls the dimming ballasts installed in the ceiling fixtures directly over the in-place wiring. Thus, OccuSwitch is more economical to install into existing building wiring systems because it does not required the installation of additional control wiring.

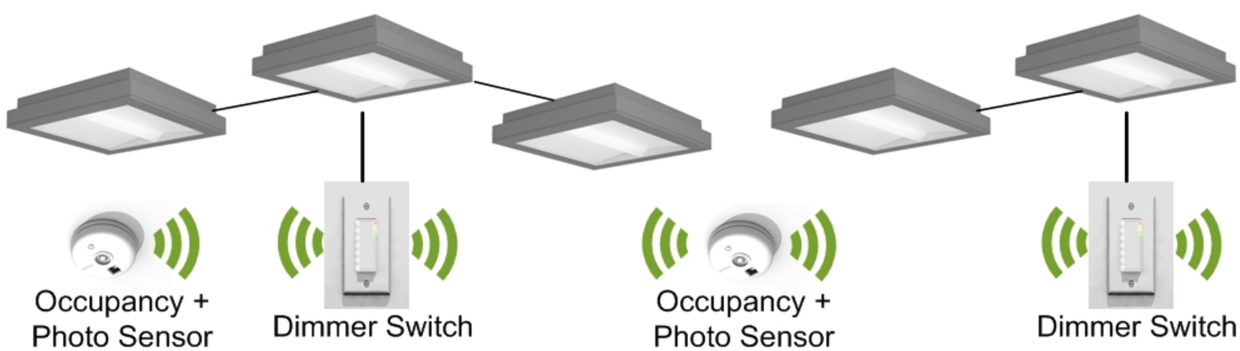



Figure 3: Schematic diagram of OccuSwitch Wireless

Figure 4: OccuSwitch wireless occupancy and photo-sensor

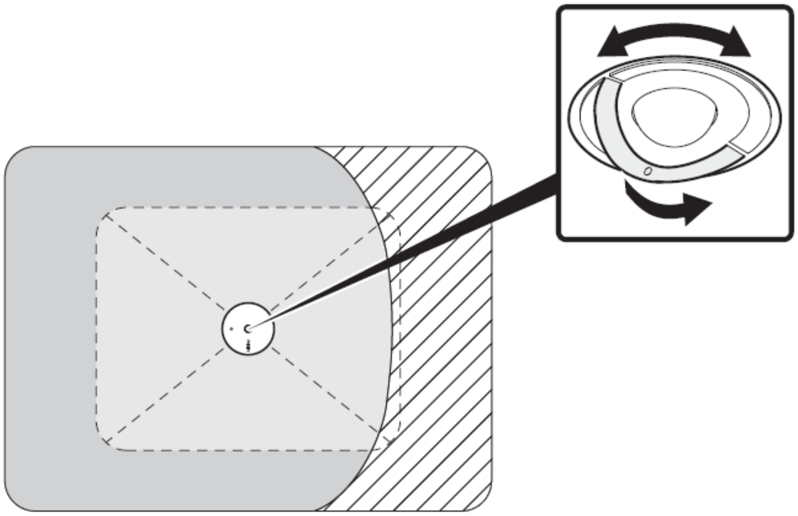


Figure 5: Adjustable rotating shield for on-site field of view adjustments

Figure 6:  OccuSwitch wireless wall dimmer

***Architecture:*** As shown in Figure 3, the system consists of two main components: a wall mounted dimmer switch and a battery-powered ceiling-mounted combination photo and occupancy sensor, which are interconnected using ZigBee PRO [3] wireless technology.  The dimmer switch controls line voltage (triac) dimming ballasts, which are wire compatible with standard ballasts, simplifying the retrofit. Multiple sensors and switches can be used to expand coverage. The system can support a wireless network of up to 16 sensors and switches (in any combination).  Secure encryption of all messages ensures network protection using a 128-bit Advanced Encryption Standard with unique keys.  The system delivers superior, reliable wireless performance in a variety of indoor applications.  OccuSwitch Wireless embodies simplicity and flexibility in its design and enables significant energy savings without the cost and complexity of fully networked solutions.

***Operation:*** Using a combination of passive infrared technology and advanced logic for detecting major and minor motion, the sensor recognizes when the room is occupied (or unoccupied), helping to eliminate the possibility of false triggers. The sensors include an adjustable rotating shield, which enables field of view adjustments for occupancy detection (Figure 5). The system adapts to accommodate varying usage patterns with built-in intelligence to automatically adjust the shut off time delay. The light level reporting frequency is dynamically adapted to save battery energy. For example, the reporting interval is longer when the space is unoccupied or when the light level is stable. On the other hand the sensor reports immediately when the light level changes by more than a predetermined threshold. Similarly, the occupancy state change is reported immediately. Thus, the system quickly responds to changes in the environment while preserving battery energy. Battery lifetime is estimated to be more than 7 years.

The occupancy sensor detects motion and the photosensor measures the light level; these are then communicated to the dimmer switch over the radio interface. The dimmer device drives the Mark 10 line voltage dimmable ballast to control the light output. When the space is unoccupied the lights are turned off. When the space is occupied the closed-loop feedback system regulates the light level close to the setpoint by dimming the artificial lights in proportion to available daylight. Unlike other fixture-mounted photosensor-based systems, the wireless photosensors can be strategically placed to sample the occupancy patterns and light levels at the appropriate locations. Since the multi-sensor is battery powered and can communicate with the wallbox dimmer wirelessly, installation labor costs can be minimized. Moreover, if the layout changes then sensors can be easily moved to take greater advantage of daylight and improve occupancy detection without requiring an electrician. OccuSwitch is compliant with applicable California Title 24 requirements.

### 2.1.3 Dynalite

***Functionality:*** Dynalite is a distributed control based building-wide lighting control system offering scene settings, personalized dimming, scheduling, occupancy sensing and daylight harvesting. This system features the reliability offered by a wired solution, an intuitive user interface and an interface to Building Management Systems (BMSs).

***Architecture:*** Figure 7 outlines the Dynalite system architecture for a multi-story application in which sensors, control panels, touch screens, time-clock, server PCs and controllers are interconnected over an RS485 network to form a complete solution. Command and status information is passed to all devices over the network using the event-based DyNet protocol. The distributed processing architecture is robust against a single point of failure. Should a single device fail, all other devices will continue to operate as normal. The broadcast event-based wired network ensures that alterations or additions can be made after installation, without the need to re-configure or rewire the entire system. It also simplifies direct network integration with LON, BacNet and IP networks.

***Operation:*** Dynalite's universal Sensor (see Figure 8 and Figure 9) combines motion detection, light level detection and receiver (for remote control). Occupancy and light sensors work together in conjunction with time clocks to implement conditional logic control. When excess natural light is detected, the electric light is switched-off in the absence of motion, but when

occupancy is detected then electric light is dimmed to avoid shadowing and provide adequate horizontal illumination on desk surfaces. Dynalite implements time-schedule based controls to eliminate unnecessary lighting energy use outside 'normal' working hours (e.g. after hours, weekends, public holiday). If off-shift employees are detected then egress paths and common areas are illuminated. The time clock can be used to trigger events by time of day, sunrise or sunset, on a specific day of the week, or on a specific date.

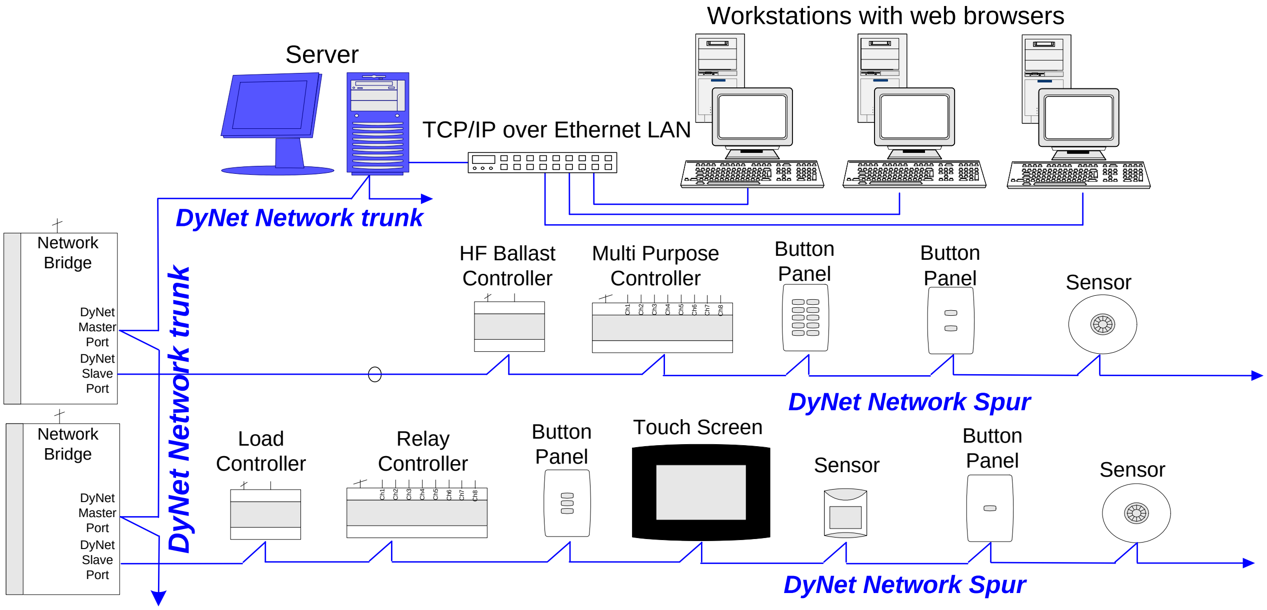



Figure 7: Architecture of the Dynalite system


Figure 8: Dynalite's universal sensor

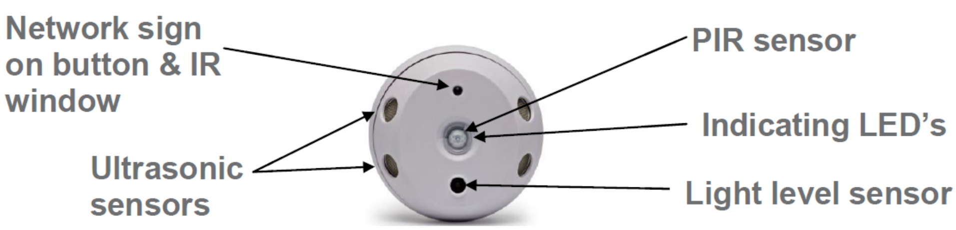



Figure 9: Dynalite's universal sensor


Figure 10: Dynalite’s load controller and user interfaces

Dynalite has an extensive range of controllers with a variety of output types, combinations and load ratings. The relay or dimmer is controlled by a microprocessor contained in the load controller. Load controllers constantly listen to the network and only respond to command messages that relate to the controller's specific configuration. Control associations are established between user interfaces and load controllers using straightforward device addressing and command techniques.

Dynalite harnesses the power of a fully networked system to collect real-time performance data for diagnosis and maintenance purposes. Dynalite also supports a number of advanced diagnostic functions, which include device online/offline status, and circuit run time tracking. Device online/offline status enables all devices to be periodically polled to determine if they are visible on the network and operating normally. Lamp run-time tracking and status reporting enable scheduled lamp replacement, which reduces life-cycle operating costs. Maintenance personnel can be automatically alerted when components fail or circuit breakers trip, which reduces downtime.

## 2.2 TECHNOLOGY DEVELOPMENT

### 2.2.1 Hybrid ILDC

The Hybrid ILDC system has been developed by PRNA using COTS components and standard communication protocols. A core system comprising wirelessly networked sensors, dimming ballasts and motorized blinds has been operational in the lab since March 2009 before the initiation of this project. Between March 2009 and March 2010 the design of the system was further refined and system was installed in several test spaces in the lab. ESTCP funding was mainly used for the following activities.

- Design and layout specification of the system and components installed at the target site.
- Procurement of the components in the desired quantities including spares.
- Engineering customization of system components to make them ready for demonstration.
- Software configuration and upgrades.
- Testing and debugging of the system components.
- Installation, on-site calibration and configuration.
- Commissioning and trouble shooting.
- Fine-tuning and remote performance monitoring.

### 2.2.2 OccuSwitch Wireless

A wired version of the OccuSwitch called Actilume has been commercially deployed since 2008. Wireless version of this system was in the advanced stages of product development when the project got started. Product was launched in the US market in 2012. ESTCP funding was primarily used for the following activities:

- Design and layout specification of the system and components installed at the target site.
- Procurement of the components in the desired quantities including spares.
- Installation, on-site calibration and configuration.
- Commissioning, trouble shooting and fine-tuning.

### 2.2.3 Dynalite

The Dynalite lighting control and energy management system is an enhancement of a proven commercial product in Europe, Asia and Australia. When the project started the system was being adapted and enhanced for the US marketplace. The product was launched in the US in 2010. ESTCP funding was mainly used for the following activities:

- Design and layout specification of the system and components installed at the target site.
- Procurement of the components in the desired quantities including spares.
- Installation, on-site calibration and configuration.
- Commissioning, trouble shooting and fine-tuning.

## 2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Table 2 provides the distinguishing characteristics of the three systems. Limitations of these systems are discussed below.

Table 2: Key features of demonstrated systems

| | **Hybrid ILDC** | **OccuSwitch Wireless** | **Dynalite** |
|---|---|---|---|
| **System architecture** | Room/area based control with building-wide connectivity | Room-based control | Distributed control building-wide connectivity |
| **Control type** | Integrated control of daylight & electric light. Link to HVAC. | Electric light control | Electric light control integrated with BMS |
| **Supported Sensors** | Sunlight intensity sensor, light/occupancy/temp sensors | Light sensors and occupancy sensors | Ceiling mounted light /occupancy sensors |
| **Scalability** | Scalable from a single room to entire building | Room by Room | Scalable from a single room to entire building |
| **Best applications** | Multi floor office buildings with daylight areas. Retrofit or new | Single offices; barracks; Retrofits; smaller budget | New construction, major renovation. |
| **In-room Connectivity** | Wireless based on ZigBee PRO standard | Wireless based on ZigBee PRO standard | Wired |
| **Building-wide connectivity** | Wired using IP over Ethernet | Not Applicable | Wired using RS 485 |
| **Cost advantage** | ++ Installation<br>++ Recommissioning | +++ Installation<br>++ Recommissioning | + Installation<br>+++ Recommissioning |
| **Energy adv.** | +++ | ++ | ++ |
| **Challenges** | Building-wide interconnect | Optimal Sensor placement | Installation skills |

By design, hybrid ILDC is suitable only for perimeter areas in the building which receive the daylight. Compared to a conventional system, more skills are needed to configure and commission the integrated system.

The OccuSwitch system, with its modular room based or area based control is suitable for small buildings where full networking is not required. OccuSwitch wireless system demonstrated at Ft. Irwin does not support building-wide connectivity. Hence, it is not suitable for centralized monitoring and control. Newer versions of OccuSwitch system currently in advanced stages of development are capable of providing building-wide connectivity and they can support centralized monitoring and control.

The Dynalite system, based on robust wired communication links, is optimized for new constructions or deep retrofit where the incremental cost of wiring is minimal since it can be

done during and together with the wiring of the rest of buildings. However, as shown in this demonstration project, the system can be effectively implemented in building with drop ceilings as well.

The Hybrid ILDC as well as the Dynalite systems are most appropriate in large buildings where centralized monitoring and controls create value by allowing features such as demand response or peak load control.

# 3 PERFORMANCE OBJECTIVES

## 3.1 PERFORMANCE OBJECTIVES

To gauge the performance of lighting control systems, we defined quantitative and qualitative performance objectives that were aligned with the objectives of ESTCP's Energy and Water program as well as DoD's broader goals of energy security, environmental stewardship and economic performance. Note that these objectives, including success criteria, were set prior to installation of three systems. The terms used in performance objectives table are defined below.

Installed Lighting Power

> The electrical power of all installed (hard wired and plugged in) fixtures at full power, which includes the lamps, ballasts, and control devices. Installed lighting power is specified in Watts.

Code Baseline Lighting Power Density (LPD)

> The maximum amount of *Installed Lighting Power* for all interior lighting systems in the target space per square foot of *lighted floor area* as allowed by the ANSI/ASHRAE/IESNA Standard 90.1-1989. LPD is specified in Watts/sq ft.

Code Baseline Lighting Energy Usage Intensity (EUI)

> The amount of energy used for interior lighting systems using the *Code Baseline LPD* and the estimated *lighting schedules*. This metric is determined as the product of the *lighted hours per workday, number of workdays per year* and *Code Baseline LPD*. In this report we assume that on an average the lights are on for 10 hrs per working day and 251 workdays in a year. EUI is specified in kWh/sq ft/yr.

Peak Lighting Power

> The peak lighting power measured on all lighting circuits averaged over the data recording period of 15 minutes, recorded over study period. Peak lighting power is specified in Watts.

Peak LPD

> The Peak Lighting Power in the building or building space per unit of lighted floor area. Peak LPD is specified in watts/sq ft.

Illumination level or illuminance

> Density of luminous flux incident on a surface. Illuminance is expressed in lux.

Workplane

> The location where a task is performed.

Work plane Illuminance

> The work plane illuminance measured at ~3 ft from the floor in lux.

Downtime

> The time duration when the lighting control system is non-responsive to manual on-off commands.

Table 3: Performance objectives

| Performance Objective | Metric | Data Requirements | Success Criteria |
|---|---|---|---|
| **Quantitative Performance Objectives** | | | |
| Reduce electrical energy consumption for lighting | Energy Use Intensity (EUI) as kWh/sq ft/yr | Metered electricity usage after lighting control installation and code baseline lighting energy | >45% reduction in EUI compared with code baseline lighting energy |
| Reduce lighting demand by better lighting design | Peak Lighting Power Density (LPD) as watts/sq ft | Metered data on peak lighting power, fixture data, floor plans and code baseline LPD | >25% reduction in Peak LPD compared with code baseline LPD |
| Reduce Carbon footprint of the lighting system | MMT/sq ft/yr | Electrical energy savings and sources of electrical energy at Fort Irwin | >45% reduction in carbon footprint compared to a building with code baseline lighting energy in the same region |
| Cost-Effectiveness | Savings-to-Investment Ratio (SIR) over a 20 year period | Data on cost elements mentioned in Table 36 including historical energy cost, energy use, operating cost savings | >2 SIR over a 20 year period |
| | Simple Payback | | <7 years Payback |
| System Reliability | System uptime | System failure notifications | No more than 3 system-wide failures per system in a 3 month time window |
| System Maintainability | Number of scheduled maintenance outages and average length | Number of scheduled maintenance actions and downtime | No more than 4 scheduled maintenance actions per system per month and no more than 8 hours of scheduled maintenance downtime per system per month. |
| | Number of unscheduled maintenance outages and average length | Number of unscheduled maintenance actions and downtime | No more than 2 unscheduled maintenance actions per system per month and no more than 4 hours of unscheduled maintenance downtime per system per month |

| | | | |
|---|---|---|---|
| Work plane Illuminance | Ft. Candle on work plane | Measured artificial light illuminance level on work plane before and after lighting control installation | >10% reduction in average deviation from the DPW requirement over the average deviations prior to upgrade. |
| **Qualitative Performance Objectives** | | | |
| Ease of installation and commissioning | Ability of installers to quickly install and commission the system | Feedback from installers on time required to install and commission system | Installer survey indicates that installers can install and commission systems with minimal training |
| User satisfaction | Level of satisfaction among users on the performance of the technology | Occupant surveys on comfort, convenience, and satisfaction with lighting and controls | User satisfaction survey indicates improved satisfaction with performance |
| System Integration | Impact of the lighting system on HVAC energy usage | Code baseline LPD, post-retrofit lighting LPD and EnergyPlus model | >5% reduction in HVAC energy compared with code baseline HVAC energy |

## 3.2 QUANTITATIVE PERFORMANCE OBJECTIVES

Quantitative analyses focused on five main metrics: energy efficiency, carbon footprint reduction, cost-effectiveness, system reliability and workplane illuminance.

### 3.2.1 Energy efficiency

Energy use intensity (EUI) and lighting power density (LPD) metrics were used to evaluate the energy conservation and demand reduction by lighting control systems. Metered data on EUI and Peak LPD after the installation of the three lighting control system were gathered. These data were compared with the code baseline EUI and code baseline LPD to determine the reduction in EUI and LPD due to advance lighting control systems. Success criteria were to demonstrate greater than 45% reduction in EUI and greater than 25% reduction peak LPD respectively.

### 3.2.2 Carbon footprint reduction

The Carbon Reduction potential of lighting control system was evaluated based on the energy savings measured at the target sites in Ft. Irwin. Since the amount of carbon dioxide emitted per unit of electricity consumed varies according to site location, we have used the conversion factor appropriate for the State of California (where Ft. Irwin is located). Using the quantified energy savings and the applicable conversion factor for Ft. Irwin, the carbon foot print reduction is derived. Success is judged against the targeted carbon footprint reduction of greater than 45%.

### 3.2.3 Cost-effectiveness

Cost-effectiveness was calculated using the energy cost savings and retrofitting costs (including costs of the design, planning, hardware, installation, commissioning, supervision, inspection and maintenance) for each installed system. The data for cost elements were collected during the demonstration.

Energy cost savings and demand cost savings were extrapolated in time to calculate cumulative savings on electricity bills. Savings in maintenance cost and utility rebates were added to derive the payback period -- when the savings is equal to the implementation costs. In addition, the lifecycle cost-effectiveness according to Savings/Investment Ratio (SIR) over a 20 year period was calculated and compared to success criteria.

Payback time and SIR were derived using the Building Life-Cycle Cost Program (BLCC5). BLCC5 is a software program developed by the National Institute of Standards and Technology (NIST) for the economic analysis of energy and water conservation and renewable energy projects in buildings.

### 3.2.4 System reliability

System failure notifications were recorded to gauge system reliability. System reliability was evaluated by assessing the system-wide failures in a pre-defined time window. Systems are designed to be fault tolerant and can gracefully recover from faults.

### 3.2.5 System Maintainability

System maintainability was judged based on number of scheduled and unscheduled maintenance actions and corresponding downtimes. The project team maintained a log of all the maintenance actions during the demonstration period. Maintainability of each system was judged based on the following criteria. Each should require no more than 4 scheduled maintenance actions per month and no more than 8 hours of scheduled maintenance downtime per month. Similarly each system should require no more than 2 unscheduled maintenance actions per month and no more than 4 hours of unscheduled maintenance downtime per month.

### 3.2.6 Workplane illuminance

An important goal of new lighting control system is to improve the lighting environment by bringing the light levels closer to the DPW specified levels. To quantify the illuminance improvements the light surveys were carried out before and after the lighting control system installation.

Light measurements were taken at representative locations at night to eliminate the effects of daylight. Statistical techniques were used to analyze the results. The average deviations from the requirements before and after the upgrades were compared. The success criterion is to reduce the average deviation from the DPW specified levels by more than 10% compared to the average deviations prior to upgrade.

## 3.3 QUALITATIVE PERFORMANCE OBJECTIVES

Qualitative analysis of performance was conducted along two axes for each system: ease of installation and commissioning, and user satisfaction. They were derived from interviews and questionnaires.

### 3.3.1 Ease of installation and commissioning

Ease of installation and commissioning was evaluated based on the feedback from installation and commissioning agents regarding time and effort required as well as problems encountered while bringing each system up to proper working condition.

### 3.3.2 User satisfaction

To gauge occupant acceptance and satisfaction with the installed lighting control technologies, LBNL administered a fifty question survey to the building occupants in the affected areas before and after the installation of the lighting controls. (Staff and management feedback was informally obtained as described in 3.3.1) This occupant survey has been used successfully in other energy efficiency demonstrations to gauge occupant satisfaction and comfort [9]. To gauge the occupant response, questionnaires were distributed to building occupants both before and after the installation of the lighting controls. In order to obtain unbiased evaluations, the surveys are voluntary and all responses are anonymous as required by the Human Subjects Protocol Committee.

### 3.3.3 System Integration

It was outside the scope of the project to study the impact of the lighting systems on HVAC energy consumption. However, upon a direct request from the committee it was agreed to use a simulation-based approach to estimate the impact of lighting on HVAC because of the difficulty in metering HVAC energy consumption in the target area of the building. Among the three lighting control systems that were demonstrated, the Hybrid ILDC system deployed in building 279 is expected to have the most influence on HVAC load due to its advanced daylight integration management capabilities. To study this effect a custom EnergyPlus building model was developed for building 279. The lighting control strategies implemented in building 279 were modeled in Matlab. Actual occupancy in building 279 was also modeled. Simulations were executed using a simulation platform that enables co-simulation of EnergyPlus and Matlab through the Building Controls Virtual Test Bed (BCVTB). This platform was utilized to perform a simulation based study to quantify the effects of lighting control systems on building HVAC energy consumption in this building.

For the other technologies, (Dynalite in portions of building 988 and OccuSwitch in building 602), the system integration study was carried out using DoE's EnergyPlus simulation platform to analyze the effects of lighting control systems on HVAC energy consumption. A generic DoE reference office building model that approximately represents buildings 602 and 988 was used in the study.

# 4 SITE DESCRIPTION

The Project Team worked with DPW to identify suitable buildings at Fort Irwin for each technology. The team visited Fort Irwin multiple times and screened the candidate buildings. The team evaluated building characteristics such as age, construction, floor-plan, orientation, daylight availability, usage scenario, amenities and window to wall ratio. Details of existing lighting infrastructure including lighting equipment, wiring conditions, light sources, control types, cabling and circuit diagrams were gathered. The building floor-plan, available circuit diagrams and electrical layouts were provided by DPW. Existing workplane illuminances were sampled and desired illuminance levels were determined. The user requirements, IT infrastructure, climate conditions, and reporting/response expectations were assessed. Preferences of DPW personnel and building occupants were taken into consideration to arrive at mutually agreeable site selection.

## 4.1 FACILITY/SITE LOCATION AND OPERATIONS

Based on above assessments, the project team selected the following buildings for the demonstration of the three lighting control systems.

1. Hybrid ILDC system was demonstrated in a section of the Building 279 covering about 1,782 sq ft.
2. OccuSwitch Wireless system demonstration was carried out in Building 602, covering almost the entire building 4,821 sq ft.
3. Dynalite system demonstration was carried out in a portion of the building 988, (Command HQ) covering approximately 7,177 sq ft out of the total building area of 22,000 sq ft.

The target area selection was mainly guided by following criteria:

1. Feasibility of isolating lighting circuits from other circuits for accurate power measurements.
2. Upgrading lighting conditions in currently underlit areas to improve occupant comfort and productivity, in accordance with DPW preferences.
3. Minimizing disruption to work schedule.
4. Feasibility of pulling cables.
5. Budget.

### 4.1.1 Hybrid ILDC system demonstration site

The building chosen for the Hybrid ILDC demonstration is a fairly old (constructed in 1950s) administrative building. The project team targeted a 1782 sq ft. section of the building made up of 8 offices—some private and some with two or three occupants—and one conference room. The target area selection was guided by availability of daylight, usage pattern, existing lighting conditions, feasibility of baseline characterization and budget. A simplified floor plan of the target space and fixture layout is shown in Figure 11.

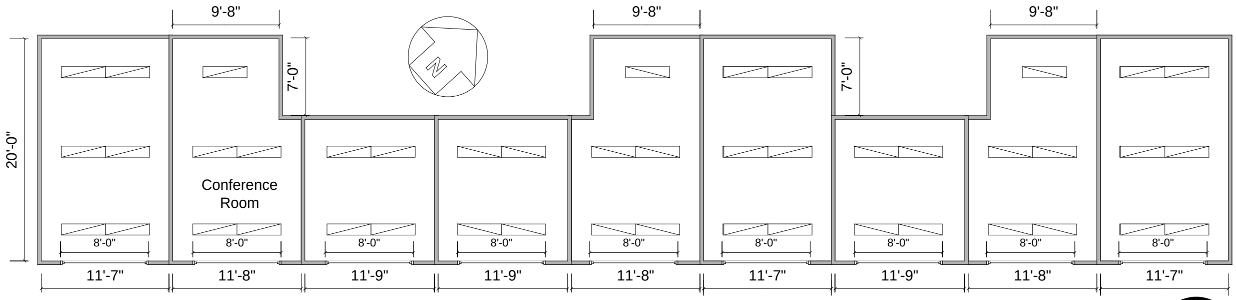



Figure 11: Simplified layout of the target space in building 279 (Dimensions are approxi[redacted])

The target rooms featured only manual ON-OFF switches at the room level. Each room targeted for retrofit has large 8’ by 5’ windows facing South-East that provide abundant daylight. Most rooms had worn vertical blinds. Some rooms have a fraction of window obstructed due to window mounted Air Conditioning units. The building has a hard ceiling, which makes wireless technology a preferred option for retrofit.

The section of the building chosen for the demonstration had 45 fluorescent T8, 32W 2 lamp fixtures. Forty-two fixtures were attached end to end in pairs, with each pair driven by a single 4 lamp fixed output electronic ballast. The remaining three fixtures were driven by 2 lamp fixed output electronic ballasts. Physical inspection of the lamps revealed that only about 54 lamps were operational out of the 90 installed lamps, probably due to a lack of maintenance. All burned out lamps were replaced prior to the baseline monitoring period. The power supply is 120 Volts AC.

The building is occupied by rotational units, with some occupants leaving for a new location after several months. Site visits and conversations with occupants suggested that while occupants perform typical office work while at their desks, work schedules often vary considerably day to day and week to week.

#### 4.1.2 OccuSwitch Wireless demonstration site

The building chosen for the OccuSwitch demonstration is a fully occupied single story office building. The building has a hard ceiling, which makes wireless technology a preferred option for retrofit. It has 14 private offices, a conference room, a library, a mechanical room, a breakroom, two restrooms, and two utility areas with exterior access. The remaining area in the center contains open plan cubicles. There are nineteen 3'4" by 2' windows on the periphery, resulting in a window to wall ratio of about 4%. Each private office has one small window that provides limited daylight, while the interior open plan office area has negligible daylight.

The project team targeted 4821 sq ft of the floor area (out of total 5000 sq ft) for lighting upgrades covering the entire building except for exterior utility rooms. Of this area, 4375 square feet are included in all energy analysis. A circuit including the exterior utility rooms, the bathroom, and the break room was excluded from analysis due to extremely different pre-retrofit and post-retrofit use patterns in the exterior utility areas, which were not included in the retrofit.

The pre-retrofit lighting system consisted of 101 fluorescent T8 32 Watt four lamp fixtures which were driven by fixed light output ballasts. A large number of lamps were intentionally removed from fixtures to save energy, causing distorted light distributions. Physical inspection revealed that only 201 lamps were installed and operational out of 404 potential lamps, bringing the installed LPD to 1.43 W/sq ft out of a possible 2.46 W/sq ft (based on benchtop measurements discussed later). Delamping was particularly severe in the open office area, in which many fixtures had one or no operating lamps. The power supply is 120 Volts AC. The building had only manual on-off switches that did not allow occupants to adjust light levels.

#### 4.1.3 Dynalite demonstration site

Building 988, the current command headquarters, is the target site for the Dynalite system. It is a single story administrative building that had only manual on-off switches prior to retrofit. It comprises of a variety of room types such as private offices, open plan offices, conference rooms, a surveillance room, a theater, a storage room and a copy room. Some of these rooms are occupied by key individuals and have the usual occupancy patterns. In its entirety, it is representative of a sizable class of administrative buildings in the DoD stock. The building has a standard drop ceiling, which makes it appropriate for the Dynalite system which requires physical cabling to network together the luminaires, sensors and controllers that make up the lighting control system. It is easier and less expensive to install control wiring into a drop ceiling than it is a hard ceiling as the latter generally requires conduit that is expensive to install in existing buildings.

The project team targeted approximately 7177 sq. ft of building 988 consisting of 7 private offices, 1 open plan office, 1 conference room, 1 surveillance room, 1 theater, 1 lobby, 2 restrooms, 1 storage room and 1 copy room. The pre-retrofit lighting in target area comprised of (85) fluorescent T8 32 W 3 lamp and (6) T8 32W 2 lamp fixtures driven by fixed output ballasts. Some areas of the building were delamped to conserve energy. Before the retrofit only 237 lamps were installed out of 267 potential lamps. Delamping was extensive in open plan office area. The open plan office area had light levels well below the code requirements causing occupants to complain about the existing lighting conditions. Power supply is 277 Volts AC.

# 5 TEST DESIGN

The project team deployed and demonstrated three complementary lighting control systems that together meet different DoD facility requirements and offer unique cost-benefit profiles. The baseline characterization, design and layout of technology components, operational testing and sampling protocols for three systems are discussed in this section. In addition, this section describes how the actually measured pre-retrofit energy use data in Buildings 602 and 988 were *adjusted* to account for changes in the lighting design (and therefore LPDs) that were requested by the client during the controls install. The use of an adjusted pre-retrofit baseline allowed the Team to isolate the effect of the lighting controls from the changes in LPD requested by DWP.

## 5.1 BASELINE CHARACTERIZATION

### 5.1.1 Code Baseline

The code baseline Lighting Power Density (LPD) is the amount of installed lighting power for the lighting systems in the target space per square foot of lighted floor area as allowed by the lighting code.

The code baseline lighting Energy Usage Intensity (EUI) is determined as the product of the lighted hours per workday, number of workdays per year and the Code Baseline LPD. It was assumed that on average the lights are on continuously for 10 hours per day on weekdays and remain off during weekends and holidays. Furthermore, to derive annual EUI, 251 weekdays per year are assumed.

The Unit Lighting Power Allowance specified in ANSI/ASHRAE/IESNA Standard 90.1-1989 is 1.81 W/sq ft for office buildings having gross lighted areas in the range of 2,001 to 10,000 sq ft. This results in a code baseline annual EUI of 4.54 kWh/sq ft/yr. In this report, the code baseline refers to this baseline. This baseline is intended to represent existing DoD lighting systems that were installed over 20 years ago and are in need of a retrofit. The 10 hour workday was selected for the project based on typical use patterns in open offices and shared spaces.

In order to compare the results with more recent code requirements, another reference was defined based on the ANSI/ASHRAE/IESNA Standard 90.1-2007. In this standard, the whole building LPD allowance for office spaces is specified as 1 W/sq ft. Based on 1 W/sq ft LPD, 10 hour work day and 251 workdays a year, the annual EUI is estimated to be 2.51 kWh/sq ft/yr. In the remainder of the report we refer to this as the 2007 code reference.

### 5.1.2 Pre-retrofit metered lighting energy use in building 279

Pre-retrofit data collection resulted in 102 complete days of data between September 2010 and January 2011. This dataset consists of 66 weekdays, 30 weekend days and 6 holidays. Incomplete days and the week from 12/25/10 to 1/2/11 were excluded from the dataset. Analysis of the weekday EUI for each circuit found no evidence of seasonal trending associated with reductions in available daylight in the winter months. Analysis also found no trending associated with weekday day of the week.

The pre-retrofit dataset had an average weekday EUI of 4.94Wh/sq ft/day, weekend EUI of 0.75Wh/sq ft/day, and holiday EUI of 0.72Wh/sq ft/day. Annual EUI was calculated from these values based on an assumed annual distribution of 251 weekdays, 104 weekend days, and 10 holidays per year. This resulted in an annual EUI of 1.33kWh/sq ft/yr. Pre-retrofit metered energy use is much lower than the code baseline in part due to a lower installed LPD (1.51W/sq ft installed compared to 1.81W/sq ft code allowance) but primarily due to much lower use patterns.

Lighting use varied widely from day to day, with many lights remaining off for long periods of time during typical work hours. This meant that daily EUI varied widely as well. Site visits and informal conversations with occupants revealed that occupancy in some areas varied considerably from day to day and that occupants sometimes worked without turning on their lights. All in all, despite a fairly high installed LPD and on-off controls at the room level only, the pre-retrofit metered dataset had a very low EUI due to very low lighting use throughout the work day. This presented a challenging baseline for the control system to improve upon.

For each week of data, the peak LPD averaged over a 15 minute interval was calculated for the study area as a whole. This dataset was checked manually for outliers but none were found. The maximum peak LPD from the pre-retrofit metered dataset is 1.26W/sq ft.

#### 5.1.3 Pre-retrofit illuminance characterization in building 279

A pre-retrofit light survey was carried out on Jan 24, 2011 between 8:00 pm and 9:00 pm. The survey was done at night to eliminate the effects of daylight, and lights were turned on at least half an hour before measurements to eliminate a warm up effect. Workplane illuminance levels were measured throughout the study areas (2 to 4 measurements on desks per room, resulting in 29 measurements overall). Exact measurement locations were documented on the building floor plan so that the process could be repeated after the retrofit. Note that the rooms were in service throughout the study period and were full of office furniture, equipment and clutter. Despite the installed low-ballast factor ballasts, illuminance levels were quite high, with measured values ranging from 520 to 958 lux.

#### 5.1.4 Pre-retrofit metered lighting energy use in building 602

Pre-retrofit data collection resulted in 72 complete days of data between September 2010 and January 2011. This dataset consists of 45 weekdays, 21 weekend days, and 6 holidays. Incomplete days and the week from 12/25/10 to 1/2/11 were excluded from the dataset. A breaker tripped early in the study period and took two weeks to be repaired, which resulted in power loss to the data acquisition equipment and resulted in less than three months of pre-retrofit data. Since use patterns remained fairly consistent during the pre-retrofit period, this time period is expected to be sufficient to capture overall trends.

Analysis of the weekday daily EUI for each circuit found no evidence of seasonal trending associated with reductions in available daylight in the winter months; this makes sense as the pre-retrofit system did not include daylight harvesting. Analysis also found no trending associated with weekday day of the week.

The pre-retrofit metered dataset had an average weekday EUI of 7.01 Wh/sq ft/day, weekend EUI of 0.18 Wh/sq ft/day, and holiday EUI of 3.36 Wh/sq ft/day. Annual EUI was calculated from these values based on an assumed annual distribution of 251 weekdays, 104 weekend days, and 10 holidays per year. This resulted in an annual EUI of 1.81 kWh/sq ft/yr.

Pre-retrofit metered energy use is much lower than the code baseline due to lower use patterns, especially in the perimeter offices, and also due to substantial delamping. Site visits and informal conversations with occupants revealed that occupants worked in extremely low light conditions, especially in the open plan office area, and that some occupants preferred these low light levels. Building management personnel requested that light levels throughout the building be brought into accordance with standard practice during the retrofit.

For each week of data, the peak average LPD was calculated for the study area as a whole. This dataset was checked manually for outliers but none were found. The maximum 15 minute peak LPD from the pre-retrofit metered dataset is 1.14 W/sq ft.

#### 5.1.4.1 Adjusted pre-retrofit lighting energy use in building 602

During the retrofit, lamps were shifted from their initial uneven distribution to a layout with two lamps in each fixture. Although almost the same number of lamps operated in pre-retrofit and post-retrofit periods (201 and 202, respectively), a large number of lamps were moved from private office areas on the periphery to open office areas where de-lamping had been more extensive. Since the open office areas have much longer operating hours and higher energy use than the perimeter spaces, this shift alone increased building's overall lighting energy use. To eliminate this effect and isolate the savings associated with the lighting controls, an adjusted pre-retrofit was calculated from the pre-retrofit metered dataset. This adjusted pre-retrofit estimates what energy use would have been with identical baseline use patterns but with the post-retrofit installed lamp layout.

To derive the adjusted pre-retrofit, the post-retrofit installed power associated with lamps and ballasts (in watts) was divided by the pre-retrofit installed power to generate a conversion factor for each circuit. The pre-retrofit metered power for each circuit was then multiplied by the circuit's conversion factor to derive adjusted power and energy estimates. This assumes that the fixtures on each circuit had similar use patterns; it is expected to be a reasonable estimate of energy use had the lamp layout been changed prior to pre-retrofit data collection.

The adjusted pre-retrofit has a calculated weekday EUI of 8.59 Wh/sq ft/day, weekend EUI of 0.25 Wh/sq ft/day, and holiday EUI of 4.72 Wh/sq ft/day. This results in an annual EUI of 2.23 kWh/sq ft/year. The adjusted pre-retrofit uses 23% more energy than the pre-retrofit metered and significantly less energy than the code baseline. The peak LPD for a 15 minute interval over the pre-retrofit study period is 1.17 W/sq ft for the adjusted pre-retrofit.

### 5.1.5 Pre-retrofit illuminance characterization in building 602

A pre-retrofit light survey was carried out on Jan 10, 2011 between 8:00 pm and 10:00 pm. Illuminance levels were measured throughout the study areas (37 measurements overall), and exact measurement locations were documented on the building floor plan so that the process

could be repeated after the retrofit. Unfortunately, due to contractor's oversight, many measurements were taken at floor level rather than at the workplane; these were included in analysis nonetheless. Note that the rooms were in service throughout the study period and were full of office furniture, equipment and clutter. Illuminance levels were quite extreme, with measured values ranging from very low (22.4 lux) to extremely high (1662 lux).

#### 5.1.6 Pre-retrofit metered lighting energy use in building 988

Metered data collection resulted in 99 complete days of data between August and December 2010. This dataset consists of 63 weekdays, 31 weekend days, and 5 holidays. Analysis of the weekday daily EUI for each circuit found no evidence of seasonal trending associated with reductions in available daylight in the winter months; though one circuit did exhibit an upward trend during the study period, however, this could not be correlated with daylight availability (see section 5.4.5 for discussion). A lack of daylight trending makes sense as the pre-retrofit system did not include daylight harvesting and most of the study area did not have access to daylight. Analysis did reveal statistically significant trending associated with weekday day of the week. Hence, weekday data were adjusted prior to annual energy calculations. (see Section 5.4.5 for discussion). This adjustment changed average weekday energy use by less than 1%.

Three circuits in the study area had constant base loads that could not be identified and that did not appear to be lighting loads. It was verified that these loads were not associated with lighting in the study areas or in the vicinity of the circuits' main lighting areas. Further, these constant loads did not appear to change during the study period. To eliminate the effect of these non-lighting loads, a constant current equivalent to the constant load was subtracted from each circuit (that had constant load) prior to analysis during both the pre-retrofit and post-retrofit periods.

The pre-retrofit dataset had an average weekday EUI of 8.02 Wh/sq ft/day, weekend EUI of 3.77 Wh/sq ft/day, and holiday EUI of 5.06 Wh/sq ft/day. Annual EUI was calculated from these values based on an assumed annual distribution of 251 weekdays, 104 weekend days, and 10 holidays per year. This resulted in an annual EUI of 2.46 kWh/sq ft/yr.

Pre-retrofit metered energy use was found to be lower than the code baseline in part due to a lower installed LPD in open plan office areas and lower use in non-office space types (e.g. theater, restrooms).

For each week of data, the peak average LPD was calculated for the study area as a whole. This dataset was checked manually for outliers, but none were found. The maximum 15 minute peak LPD from the pre-retrofit metered dataset is 0.77 W/sq ft.

##### 5.1.6.1 Adjusted pre-retrofit lighting energy use in building 988

During the retrofit, several areas in which lamps had been removed were re-lamped. In particular, in the large open office area that constitutes much of the study area, three lamp fixtures had been de-lamped to two lamps per fixture. Delamping had reduced illuminance levels and caused occupant complaints about light conditions. To address this, three lamps per fixture were installed during the retrofit. Further, pre-retrofit fixed output ballasts with fairly low ballast factors (0.9 and 0.88) were replaced with dimmable ballasts with higher ballast factors of

1.0. This increased the available light output but also increased the installed operating power. Finally, four parabolic lensed troffer 3 lamp fixtures were installed in the surveillance room to address glare.

The adjusted pre-retrofit has a calculated weekday EUI of 12.14 Wh/sq ft/day, weekend EUI of 5.76 Wh/sq ft/day, and holiday EUI of 7.73 Wh/sq ft/day. This results in an annual EUI of 3.73 kWh/sq ft/year. The adjusted pre-retrofit uses 47% more energy than the pre-retrofit metered and significantly less energy than the code baseline. The peak LPD over a 15 minute interval is 1.11 W/sq ft for the adjusted pre-retrofit dataset.

#### 5.1.7 Pre-retrofit illuminance characterization in building 988

A light survey carried out by DPW before the project initiation had revealed that light levels at some locations in the open plan office area were lower than IESNA recommendations. During informal conversations, some occupants complained about the poor lighting environment. Building management personnel requested that light levels throughout the study area be brought into accordance with standard practice during the retrofit.

A pre-retrofit light survey was carried out on Dec 20, 2010 after 7:00 pm. The survey was done at night to eliminate the effects of daylight. Lights were turned on at least half an hour before the measurements to eliminate a warm up effect. Illuminance levels were measured throughout the study areas (32 measurements overall), and exact measurement locations were documented on the building floor plan so that the process could be repeated after the retrofit. Of these measurements, 10 were taken in private offices and 6 in the open office area; other measurements were not included in analysis. Unfortunately, two open office measurements were taken at floor level rather than at the workplane, these were included nonetheless. Note that the rooms were in service throughout the study period and were full of office furniture, equipment and clutter. Illuminance levels varied widely but were mostly above 500 lux in private offices and between 300 and 400 lux in the open office. Open office light levels did not have as wide a range as light levels recorded by DPW in the earlier survey; unfortunately, DPW’s measurement locations could not be correlated to exact measurement locations from this survey.

## 5.2 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

### 5.2.1 Hybrid ILDC

Forty-five existing 2 lamp fixtures operated with fixed output ballasts were replaced by 45 new Wrap 9” x 48” Prismatic Surface Wrap Lens fixtures made by Philips. Each fixture was equipped with a 2x28T5/UNV DIM universal dimmable ballast, which operates with 64W input power and a ballast factor of 1.0. The fixture was custom fitted with a ZigBee radio module, a 0-10 Volt ballast controller and accessories (e.g. power adapter and relay switch), which increased input power by approximately 2W. Each fixture housed two Philips 28W/841 T5 HE ALTO UNP fluorescent lamps. Additional equipment including 9 motorized venetian blinds, 24 ceiling mounted wireless occupancy and light sensors, 9 window mounted photo sensors, 9 zone controllers, 9 touch screen control panels, database server, UPS, Ethernet Switches and CAT5e cables were installed. Tablets, zone controllers and database server were loaded with custom software. Lighting circuits and data logging equipment did not change during retrofit.

Primary commissioning activities included populating the database, configuring devices, calibrating sensors, tailoring the dimming algorithm, adjusting glare control parameters, capping ballast output and setting up networks. Ballast output was capped well below the maximum level in order to reduce light levels to acceptable values; this resulted in 36W of input power per fixture. Note that the database does not collect or store any personally identifiable information about the occupants in order to protect their privacy.

Pre-retrofit, post-retrofit, and tuned installed LPDs are summarized below in Table 4. Note that since the pre-retrofit system had low-BF ballasts, the installed power increased during the retrofit despite the switch to 28W lamps. The installed power was then tuned significantly by capping ballast output in order to reduce light levels.

The project team decided to keep the fixture layout and number of lamps the same to avoid the additional cost of rewiring and painting. F28T5 lamps with a BF of 1.0 were installed to maintain the flexibility to increase light levels in the future to accommodate future changes in space usage, even though this made the maximum installed light levels much higher than current requirements. As a result, the lamp and ballast upgrades increased the installed lighting power. The maximum light output of the new system was then capped to meet current illuminance requirements. If future increases in light outputs were not envisaged, then reducing the lamp count and/or using a more efficient lamp and ballast combination to meet the current lighting requirement would have improved performance in this demonstration.

Table 4: Summary of installed lighting system and LPD in building 279

| | Pre-retrofit | Post-retrofit installed | Post-retrofit after tuning |
|---|---|---|---|
| Lamp type (2 lamps per fixture) | F32T8 | F28T5 | F28T5 |
| Number of fixtures | 45 | 45 | 45 |
| Installed power (W) | 2547 | 2880 | 1620 |
| Floor area (sq ft) | 1782 | 1782 | 1782 |
| Installed LPD (W/sq ft) | 1.43 | 1.62 | 0.91 |

#### 5.2.2 OccuSwitch Wireless

One hundred and one existing 4 lamp T8 fixtures were converted to 2 lamp dimming fixtures. Each fixture was equipped with a 2 lamp line voltage (triac) dimming ballast and two T8 Cool White (4100K, 85 CRI) 32W Philips fluorescent lamps. The installed power after the retrofit was 68W per fixture. Control equipment, including 31 ceiling-mounted wireless occupancy and light sensors, 27 dimmer wall switches (adding 3 new gang single gang locations), and 3 dimming power extenders were installed. Lighting circuits did not change during the retrofit. Occupancy sensors were strategically placed in private offices to avoid false positive detection due to occupant movement in the adjacent hallways. The sensors include an adjustable rotating shield that enables field of view adjustments for occupancy detection.

Primary commissioning activities included configuring devices, calibrating sensors, capturing setpoints, capping ballast output and setting up networks. The occupancy timeout on all sensors was set to 15 minutes. Note that 15 minutes is the lower bound for the timeouts; the actual timeout period is dynamically adjusted by the algorithm built into the sensors to avoid false negatives. Pre-retrofit delamped, and post-retrofit installed LPDs are summarized in Table 5. The pre-retrofit installed LPD is calculated from benchtop measurement of the installed ballasts operating 0, 1, 2, 3, or 4 lamps. Measurement results were summed across the study space based on the distribution of fixtures and lamps installed in each fixture.

Table 5: Summary of installed lighting system and LPDs in building 602

| | Pre-retrofit delamped | Post-retrofit installed |
|---|---:|---:|
| Lamp type | F32T8 | F32T8 |
| Number of lamps | 201 | 202 |
| Installed power (W) | 5536 | 5440 |
| Floor area (sq ft) | 3723 | 3723 |
| Installed LPD (W/sq ft) | 1.49 | 1.46 |

### 5.2.3 Dynalite

Eighty five existing fluorescent T8 32 W three lamp fixtures operated with fixed output ballasts were converted to 3 lamp dimming fixtures. Each fixture was equipped with a 3 lamp DALI dimming ballast. Each fixture housed (3) T8 Cool White (4100K, 85 CRI) 32W Philips fluorescent lamps. Six existing T8 32W two lamp fixtures driven by fixed output ballasts were converted to DALI dimming ballasts. These fixtures were fitted with (2) T8 Cool White (4100K, 85 CRI) 32W Philips lamps. Four new three lamp DALI ballast driven fixtures were installed in surveillance room to address glare issue.

Table 6: Summary of installed lighting system and LPDs in building 988

| | Pre-retrofit delamped | Post-retrofit installed |
|---|---:|---:|
| Lamp type | F32T8 | F32T8 |
| Number of lamps | 228 | 279 |
| Installed power (W) | 6717 | 9409 |
| Floor area (sq ft) | 7177 | 7177 |
| Installed LPD (W/sq ft) | 0.94 | 1.31 |

Additional equipment including 31 ceiling mounted occupancy and light sensors, 17 wall stations, 1 DALI load controller, 1 DALI sniffer, 1 server PC, Dynet cables and DALI cables were also installed. Sensors were placed in rooms in a way to minimize false positives from occupancy of hallways as well as placed such that light from fixtures does not directly illuminate the face of the sensor. The sensors include an adjustable rotating shield that allows for masking of a specific direction for occupancy detection. Installers removed line power switch loop and reconnected as continuous power to the associated ballasts. Lighting circuits and data logging

equipment did not change during retrofit.  DLIII server software and Mapview software were loaded on the PC.  Pre-retrofit  delamped, and post-retrofit installed LPDs are summarized in Table 6.

The sensor and wall controls were commissioned to power lights when the wall control panel is pressed. Lights remain on while the office(s) are occupied. The light levels were tuned to DPW specified levels in the open office area as well as the private offices. The private offices on the perimeter of the building were also commissioned for daylight harvesting to maximize energy savings when natural light is available. The timeout for occupancy on most sensors was set to 20 minutes.  If the sensor times out, the light output drops before powering off completely. This allows occupants to react during the warning period in case of a false unoccupied status.  If any motion is detected during warning period then light output will increase back to previous level.

## 5.3 OPERATIONAL TESTING

### 5.3.1 Planning

Immediately after the project initiation, the processes to comply with contractual obligations were put in place.  Adherence to these processes was monitored throughout the project execution.  The planning phase began with site surveys and user requirements analysis.  In this phase, the target areas were identified and baseline lighting power metering equipment were set up.  Internet connections for remote monitoring were also setup.  The detailed system configurations including system type, area of coverage, location, type and number of control equipment, sensors, and communications links to be deployed at the site were determined.  Each system configuration was quantitatively specified and detailed schematics were prepared.  Each technology configuration underwent any required engineering customization.  Regulatory issues were addressed.  Software were upgraded and configured.  The requisite systems and components were produced in the specified number, including spares, and delivered to the base in time for installation.

### 5.3.2 Prepare for system installation

Design documents and layout plans were developed for the installation of lighting control systems and applicable light sources.  Request for quotations were issued to local contractors, responses were evaluated and electrical contractor was selected. A detailed schedule of installation and commissioning plan was prepared.  A checklist of installation and commissioning tasks was prepared.  Permissions were requested from respective building managers to perform installations. Escorts were arranged by building manager to oversee the work.  In parallel, a pre-retrofit user satisfaction survey was administered.  The pre-retrofit light level survey was also performed.

### 5.3.3 Install and commission systems

Guidance was provided to installers to facilitate quick installation of the systems.  Safety protocols were developed to maintain work areas free from hazards.  Systems were installed on site during after hours to minimize disruptions.  Occupant materials and furniture were protected

from damage and work areas were left with no trace or residues from work. Contractor's work was supervised for quality control.

Systems were commissioned by commissioning engineers. Commissioning steps include identifying, addressing and establishing communication between sensors, ballasts, switches and other devices. Furthermore, scenes and presets were programmed. Sensors and control strategies were field tested and calibrated to derive the optimal placement and settings for the best system performance. Occupancy sensor sensitivity and time delay, photo-sensor set points, dead-bands, light dimming rates and dimming profiles were field calibrated. Functional performance tests were conducted to verify and validate the performance of the system. Corrective measures were applied to remedy any non-compliance found during testing. Quantitative and qualitative feedback was gathered using the installer surveys to obtain data on the time, effort and skill required to install and commission the systems.

### 5.3.4 Conduct demonstration

Users were shown a live demonstration on how to operate the system. A walk through with building managers and DPW staff was arranged. A service contract was signed with the local contractor to provide on-site technical support. Customer service contact phone numbers were set up and provided to DPW and building managers. Service call handling processes and service dispatch routines were put in place to ensure the shortest possible response time. Any customer requests were promptly addressed. A log of maintenance activities and associated downtime was maintained by project team members. DPW staff and building managers were kept informed about the status of various activities. Power metering data collection continued throughout the demonstration. Post-retrofit light survey and user satisfaction survey were administered during the demonstration phase.

Table 7: Schedule of main activities

| Activity | **Date** | | |
|---|---|---|---|
| | **Building 988** | **Building 602** | **Building 279** |
| Plan demonstration | 8/1/2010 | 8/1/2010 | 8/1/2010 |
| Prepare for system installation | 11/1/2010 | 11/1/2010 | 11/1/2010 |
| Pre-retrofit user satisfaction survey | 12/2010 | 12/2010 | 12/2010 |
| Pre-retrofit light level survey | 12/20/2010 | 1/10/2011 | 1/24/2011 |
| Begin installation and commissioning | 12/1/2010 | 1/24/2011 | 1/24/2011 |
| Complete installation and commissioning | 2/25/2011 | 3/11/2011 | 4/1/2011 |
| Installer feedback survey | 4/25/2011 | 4/25/2011 | 4/25/2011 |
| Begin data collection | 5/1/2011 | 5/1/2011 | 5/1/2011 |
| Post-retrofit light level survey | 6/29/2011 | 6/26/2011 | 4/13/2011 |
| Post-retrofit user satisfaction survey | 9/2011 | 9/2011 | 9/2011 |
| Demonstration End | 12/23/2011 | 12/23/2011 | 12/23/2011 |

## 5.4 SAMPLING PROTOCOL

### 5.4.1 Data acquisition

Power metering and data logging equipment were installed by project team personnel (in cooperation with DPW staff) on local distribution boards to collect detailed data on lighting energy utilization. The lighting circuits were isolated from other loads and current was directly metered with true RMS current transducers (CTs) (see Appendix I for equipment calibration and quality assurance sampling procedure). Software installed on onsite laptops read current levels from the CTs every 6 seconds and averaged and recorded these values every ten readings. The resulting data files consist of current readings on each circuit at one minute intervals. A separate data file was collected for each building for each day of data.

At the end of each day, data files were automatically transferred to project team personnel through an online file sharing and backup program. This program maintained copies of all data files (appropriately named with building and date information) on the laptops in all three buildings and on LBNL computers. File transfer was verified on a daily basis (weekdays only). Files were screened for completeness on a weekly basis with a processing program created for this purpose.

Energy data was analyzed biweekly and a summary report was circulated to the project team on an approximately monthly basis. At least three months of pre-retrofit data and at least six months of post-retrofit data were targeted, though these targets were not met in some cases due to power failures, equipment malfunctions caused by lightning strikes, and other issues (see performance assessment section 6 for more information). Data acquisition continued during the retrofit and commissioning periods, though data from these periods are not included in final analysis.

Table 8: Data collection for quantitative metrics

| Quantitative metric dataset | Pre-retrofit sampling | Post-retrofit sampling |
|---|---|---|
| Current readings on each lighting branch circuits, recorded at 1 minute intervals (as average of 10 evenly spaced spot readings) | At least 3 months of daily data files for each building | At least 6 months of daily data files for each building |
| Workplane illuminance readings in offices and conference rooms | At least 20 readings per building | At least 20 readings per building |

### 5.4.2 Illuminance survey

A light level survey was carried out before and after the lighting system retrofit by the electrical contractor and/or project team personnel. Workplane illuminance levels were measured in open offices, private offices, and conference rooms throughout the study areas. Measurements were taken at night to eliminate the effects of daylight. A minimum of 20 measurements were taken in each building, though some of these were eliminated from analysis (see performance assessment

sections for more information). Exact measurement locations were documented for pre-retrofit measurements and the process was repeated after the upgrades. Measurement locations and values were recorded on building floor plans and circulated to project team personnel for analysis.

### 5.4.3 Installer survey

Ease of installation and commissioning was evaluated based on the feedback from the two key installation and commissioning agents. This feedback focused on the time and effort required to perform the work as well as on problems that came up during the process. Feedback was solicited via phone interviews with installers by project team personnel. Phone interviews were conducted in April 2011 and asked installers to rate the difficulty of various tasks, agree or disagree with several statements regarding the work they performed, and provide free response comments and feedback. The interview script is included in Appendix F.

### 5.4.4 Occupant satisfaction survey

Online occupant satisfaction surveys created by Pacific Northwest National Laboratory with input from LBNL were emailed by DPW staff to occupants in all three buildings before and after each retrofit. The surveys seek to assess occupants' qualitative assessments of their office lighting and controls. The number of people emailed and the number of responses received were recorded for each building. Responses were collected separately for each building in an online database. All responses were recorded anonymously and analyzed in aggregate. Post-retrofit surveys took place at least four months after the retrofits were completed in order to reduce the effects of bias associated with occupants' unfamiliarity with the new system. When necessary, follow-up reminder emails were sent out to encourage more occupants to take the survey. The survey contains about 50 multi-point rating and multiple choice type questions, some room for comments, and two free response questions at the end. Occupants are asked to describe their workspace, lighting, and controls, and then to respond to qualitative questions about their workspace and overall office light conditions.

Pre-retrofit surveys were administered in December 2010, just before work began. Post-retrofit surveys were conducted in September 2011, several months after the retrofits were completed. The survey was moved to a new server in the summer of 2011, which meant that two slightly different versions of the survey were administered. The initial version of the survey, which was used during the pre-retrofit period, is included in Appendix G. The post-retrofit surveys were streamlined to make questions and graphics clearer, and a few questions from the initial survey were excluded. The slight modifications are not expected to have made a difference in occupant responses.

### 5.4.5 Trending

Anova tests were conducted at the building level on the pre-retrofit and post-retrofit datasets to evaluate the possible effect of day of the week on energy use. Daily energy use datasets for Mondays, Tuesdays, Wednesdays, Thursdays, and Fridays were analyzed to evaluate the null

hypothesis that there was no trend associated with day of the week on weekdays. This resulted in the following:

- The null hypothesis of no trend associated with day of the week was disproved at the 10% level for building 279 during the post-retrofit period.
- The null hypothesis of no trend associated with day of the week was disproved at the 5% level for building 988 during the pre-retrofit period.
- The null hypothesis was not rejected at a significant level in any other case.

Based on this assessment, weekday means and standard errors were recalculated using the data for each weekday day of the week for building 279 during the post-retrofit period and for building 988 during the pre-retrofit period. These corrected means were used in annual energy use calculations and in statistical significance tests.

Anova tests were conducted to characterize monthly variations in weekday energy use at the circuit level to identify seasonal trends. While the Anova tests revealed significant variation from month to month in many cases, these appeared to potentially be consistent with daylight availability in only three cases which are discussed below. In remaining areas with and without access to daylight, the monthly variation did not appear to correlate with daylight availability. This can be attributed to wide variations in occupancy and use patterns in many parts of the study areas over the course of the year. Data were not adjusted based on these non-daylight trends, of which not enough is known to make reasonable adjustments. The three cases that did exhibit trends potentially associated with daylight availability are discussed below:

- In building 988, circuit 14, weekday energy use exhibited a very strong upward trend over the course of the pre-retrofit metering period, from late August through mid-December. If this limited dataset is fit to an annual seasonal trend associated with a sine curve, the result is a trend line with extremely large amplitude and peak energy use near the spring equinox. Based on this mismatch between the trend's peak and actual daylight availability, and taking into consideration the fact that the building did not have daylighting controls installed during this period, we must conclude that we do not know how much of this trend is attributable to daylight patterns. As a result, we cannot confidently adjust the data for seasonal trending. It appears likely that occupancy and operational changes rather than seasonal trending are the main cause of the energy use shift.
- In building 988, circuit 14 and circuit 16, post-retrofit weekday energy use appears to exhibit weak seasonal trends. Both trend lines are somewhat offset from annual daylight availability patterns based on the available data, and there is a large amount of variation in both datasets. Given the uncertainty in trend analysis due to the short study period and the lack of strong trending that clearly corresponds to daylight availability, not enough information was available to adjust the data for seasonal trending. Had adjustments been made based on a best fit sine curve from the available data, post-retrofit energy use in the building as a whole would have increased by slightly more than one percent.

Weekdays, weekends, and holidays were analyzed separately. The distribution of these data types in each dataset were taken into account when calculating annual EUI.

### 5.4.6 Analysis Assumptions

All energy calculations were based on the following assumptions:

- Estimated power factor = 1.0. Since power factors are generally lower for dimmed ballasts, this is a conservative assumption with respect to energy savings.

- Estimated voltage = specified panel voltage (277V for building 988, and 120V for buildings 279 and 602). This is not expected to generate bias in results.

- The annual distribution of days is 251 weekdays, 104 weekend days, and 10 holidays.

- The carbon footprint of lighting energy usage is derived using the annual non-baseload output emission rates applicable to Ft. Irwin. In the WECC California sub-region, the annual non-baseload output emission rates for $CO_2$ is 1.045 lb/KWh (Year 2007 GHG Annual Output Emission Rates, EPA). This emission rate was used in all carbon footprint calculations.
- The IESNA recommended workplane illuminance is 500 lux for private offices and 300 lux for open office cubicles. These are also DPW's illuminance requirements. Since a certain amount of illuminance variation can occur without negatively affecting occupants, this analysis used a target illuminance range to evaluate light levels. The range was defined as follows based on the understanding that a proportional rather than absolute increase and decrease in illuminance will have roughly equivalent effect on an occupant:

  > The acceptable range is defined as illuminance levels of [2t/3, 3t/2], where t is the target illuminance (500 lux or 300 lux). This makes the acceptable range 333-750 lux in private offices and conference rooms and 200-450 lux in open office spaces.

# 6 PERFORMANCE ASSESSMENT

This section presents the in-depth analysis of the system performance data obtained during the demonstration. Results are compared against the performance objectives stated in section 3. Insights gained from demonstration are summarized and potential for further improvements in system performance are discussed.
As stated in the executive summary, the lighting control systems were designed, developed and deployed by Philips in the three buildings indicated. All performance measurements, interpretation and analysis were carried out independently by LBNL as reported in this chapter.

## 6.1 Energy Performance Summary for All Monitored Buildings

The energy performance measured in buildings 279, 602 and 988 before the lighting controls retrofits (the pre-retrofit period) and during the first post-retrofit period immediately after the controls installation is summarized in Table 9. These results are given in more detail in the following section of this report. Note that the code baseline includes no energy use on weekends and holidays, so comparisons to the code baseline on these days are not included.

Table 9: Energy performance results

| | Building | 279 | 602 | 988 |
|---|---|---|---|---|
| Weekday EUI (Wh/sq ft/day) | Pre-retrofit metered | 4.94 | 7.01 | 8.02 |
| | Adjusted pre-retrofit | N/A | 8.59 | 12.14 |
| | Code baseline | 18.1 | 18.1 | 18.1 |
| | Post-retrofit metered | 3.28 | 6.71 | 8.68 |
| Weekday EUI percent savings compared to… | Pre-retrofit metered | 33.7% | 4.3% | -8.2% |
| | Adjusted pre-retrofit | N/A | 22.0% | 28.5% |
| | Code baseline | 81.9% | 62.9% | 52.0% |
| Annual EUI (kWh/sq ft/yr) | Pre-retrofit metered | 1.33 | 1.81 | 2.46 |
| | Adjusted pre-retrofit | N/A | 2.23 | 3.73 |
| | Code baseline | 4.54 | 4.54 | 4.54 |
| | Post-retrofit metered | 0.96 | 1.74 | 2.60 |
| Annual EUI percent savings compared to… | Pre-retrofit metered | 27.7% | 4.2% | -5.7% |
| | Adjusted pre-retrofit | N/A | 22.2% | 30.3% |
| | Code baseline | 78.9% | 61.8% | 42.8% |

## 6.2 PERFORMANCE OF HYBRID ILDC IN BUILDING 279

### 6.2.1 Reduce lighting demand

The post-retrofit dataset used in energy analysis consists of 205 days made up of 140 weekdays, 59 weekend days, and 6 holidays that were recorded from May to December 2011.

Peak LPD was calculated for each week of data collected. No outliers were identified for either the pre-retrofit or the post-retrofit data. These datasets resulted in a peak pre-retrofit metered LPD of 1.26W/sq ft and a peak post-retrofit metered LPD of 0.73 W/sq ft.

Table 10: Building 279 peak LPD results

| | | | | Percent savings compared to… | |
|---|---|---|---|---|---|
| | Pre-retrofit metered | Post-retrofit metered | Code baseline | Pre-retrofit metered | Code baseline |
| Peak LPD over a 15 minute period (W/sq ft) | 1.26 | 0.73 | 1.81 | 42% | 60% |

The goal was to demonstrate at least a 25% reduction in peak LPD compared to code baseline. The results show 60% savings over code baseline, substantially exceeding the target. The retrofit also resulted in a peak LPD 42% lower than the pre-retrofit metered peak and 27% lower than a code baseline peak corresponding to 2007 reference code requirements, which has a maximum LPD of 1.0W/sq ft.

### 6.2.2 Reduce electrical energy consumption for lighting

Table 11: Building 279 EUI results

| | | | | Percent savings compared to… | |
|---|---|---|---|---|---|
| | Pre-retrofit metered | Post-retrofit metered | Code baseline | Pre-retrofit metered | Code baseline |
| Weekday energy use intensity (Wh/sq ft/day) | 4.94 | 3.28 | 18.1 | 33.7% | 81.9% |
| Weekend energy use intensity (Wh/sq ft/day) | 0.75 | 1.24 | 0 | -65.3% | N/A |
| Holiday energy use intensity (Wh/sq ft/day) | 0.72 | 1.00 | 0 | -38.9% | N/A |
| Annual energy use intensity (kWh/sq ft/yr) | 1.33 | 0.96 | 4.54 | 27.7% | 78.9% |

Daily and annual energy results are presented below in Table 11. Annual EUI is calculated from average daily EUIs based on assumed 251 weekdays, 104 weekend days, and 10 holidays per year. For the post-retrofit data, which exhibited statistically significant variation associated with weekday day of the week, weekday EUI was calculated as an average of the EUI associated with each weekday day of the week.

Analysis of the post-retrofit dataset results in an average weekday EUI of 3.28 Wh/sq ft/day, weekend EUI of 1.24 Wh/sq ft/day, and holiday EUI of 1.00 Wh/sq ft/day. As shown in Table 11, these values correspond to an annual EUI of 0.96 kWh/sq. ft/yr, resulting in 79% annual

energy savings compared to the code baseline, 62% savings compared to the 2007 code reference of 2.51 kWh/sq ft/yr, and 28% annual savings compared to the metered pre-retrofit.

The goal was to demonstrate at least a 45% reduction in annual EUI compared to code baseline lighting EUI. The results demonstrated 79% savings in annual EUI over the code baseline, significantly exceeding the target.

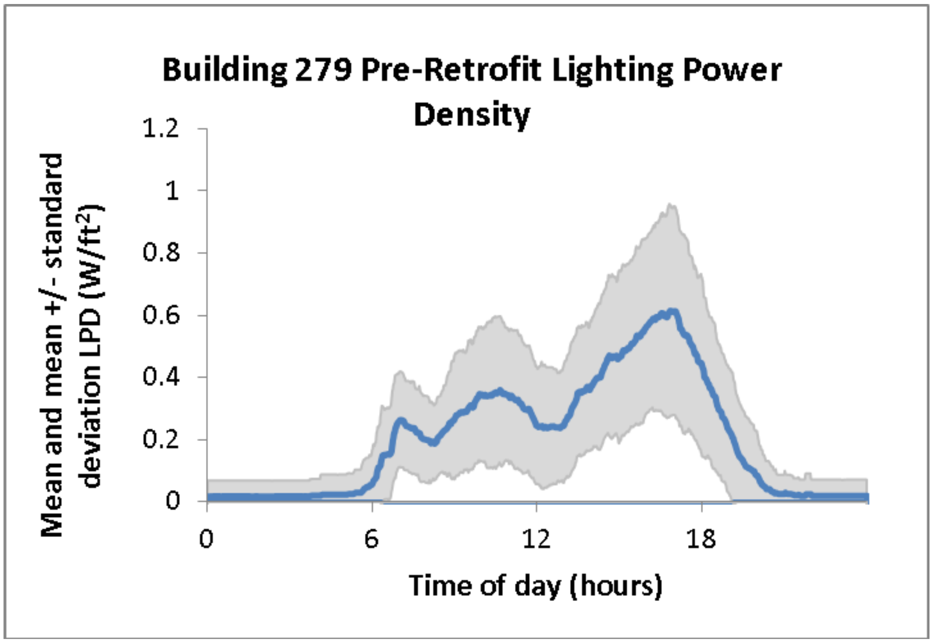



Figure 12:Pre-retrofit metered LPD in building 279

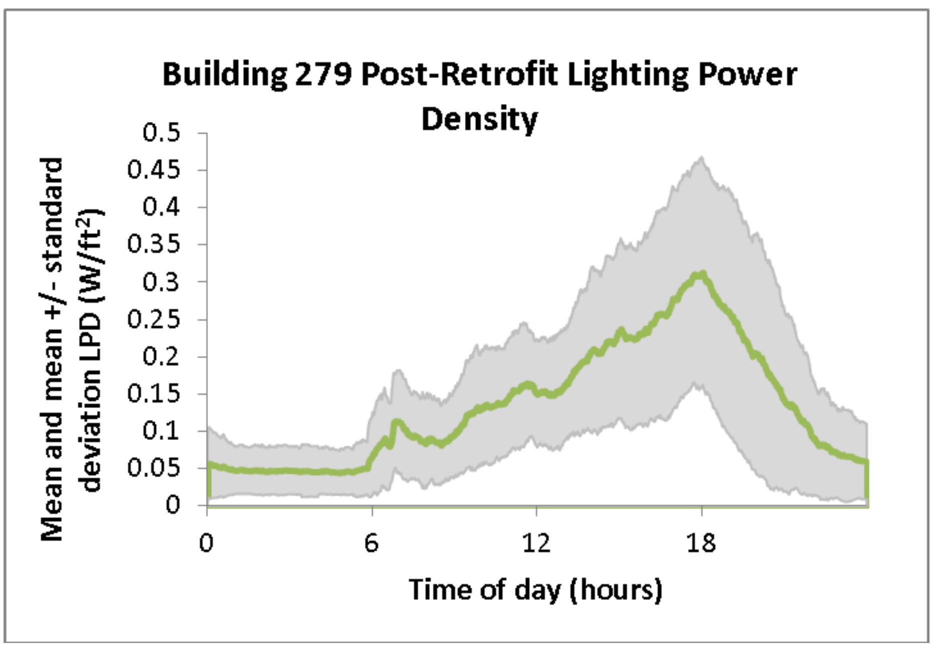



Figure 13:Post-retrofit metered LPD in building 279

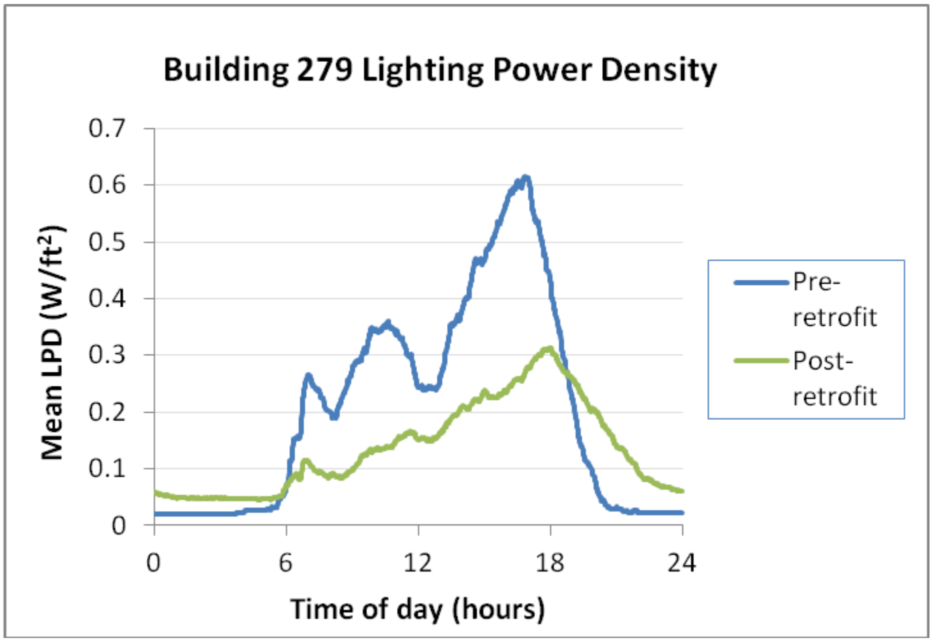



Figure 14: Mean weekday metered LPD during the pre-retrofit study period (blue) and post-retrofit study period (green) in building 279.

Mean weekday metered LPDs are shown in Figure 14 for the pre-retrofit and post-retrofit study periods. In both cases, the mean operating LPD stays far below the maximum available LPD (1.43W/sq ft pre-retrofit and 0.91W/sq ft post-retrofit tuned) throughout the day. Post-retrofit LPDs in particular are extremely low. The retrofit reduced mean weekday operating LPD significantly during work hours, largely due to tuning and daylight harvesting. However, it increased after-hours and weekend LPD somewhat due to standby power associated with the control and communication equipment.

The distributions of pre-retrofit and post-retrofit weekday metered EUIs are shown below in Figure 15. Post- retrofit mean weekday energy use decreased by 34% due to reduced operating power throughout the day. On the other hand, mean weekend and holiday EUIs increased by 65% and 39%, respectively, largely due to standby power; this eroded some of the weekday energy savings. Overall, however, weekday energy use made the dominant contribution to annual energy use during both study periods. Figure 15 shows that post-retrofit system shifted weekday EUI distribution towards the lower end (left).

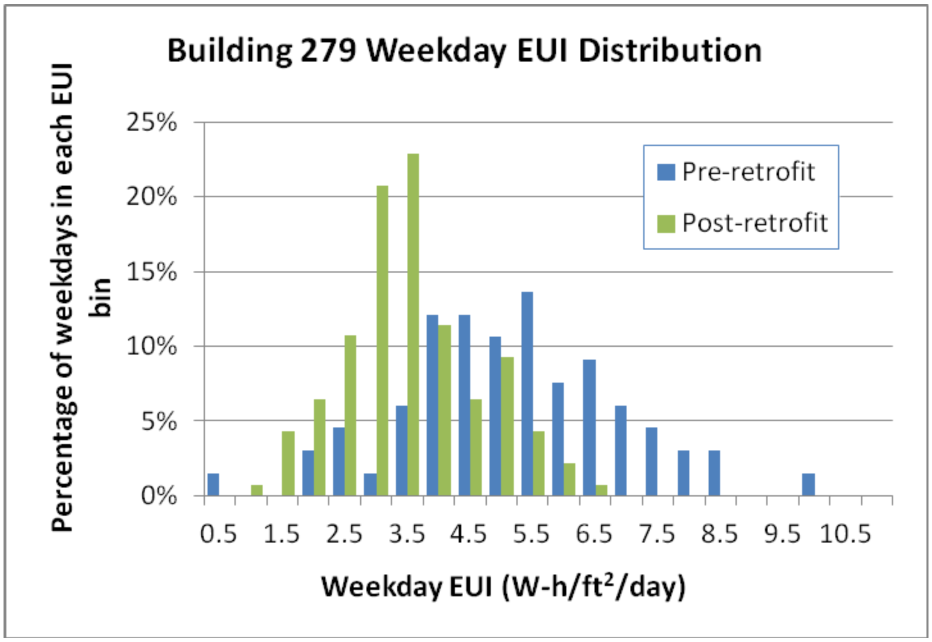



Figure 15: Distribution of weekday EUIs for the pre-retrofit (blue) and the post-retrofit study period (green) in building 279

The fixture retrofit, light level tuning and daylight harvesting contributed to the overall savings. Several factors that inhibited savings in this demonstration but can allow for additional energy savings in wide scale applications are discussed below.

6.2.2.1 Occupancy patterns and occupant behavior

Very low metered light use made achieving deep savings a challenge. Note that the pre-retrofit installed LPD was 1.43 W/sq ft and pre-retrofit metered average weekday EUI is 4.94 Wh/sq ft/day. Since the lights could not dim, we can estimate that on average a room's lights remained on for 3.45 hrs per work day. Post retrofit occupancy data analysis revealed that on an average the rooms were occupied for more than 8 hrs on weekdays during post retrofit study period. The large deviation between pre-retrofit average lights on duration and post-retrofit (metered) average occupancy duration is due, in part, to energy conscious occupants working without turning their lights on during the pre-retrofit period. Since these spaces are occupied by rotational units, it is conceivable that post-retrofit occupants had a different work profile that required them to spend less time in their offices compared to pre-retrofit occupants.

It is worth noting that the peak pre-retrofit metered LPD for the space (1.26 W/sq ft) never reached the installed value of 1.43 W/sq ft. This means that the lights were never simultaneously on for a 15 minute time interval in all 9 rooms during the pre-retrofit metering period. This observation supports the thesis that occupants often worked with their lights turned off. Further analysis of pre-retrofit metered data showed that lights were very rarely left on overnight, suggesting that occupants typically turned lights off when leaving a space. Low pre-retrofit light use and disciplined occupants generally correspond to low levels of wasted light, leaving the control system limited room for improvement.

#### 6.2.2.2 Occupancy sensing limitations

In this demonstration, the combination of installed controls, occupant behavior and building layout meant that in some cases automated occupancy controls increased energy use compared to manual controls. First, the control system automatically turns the lights on when a space becomes occupied, which increases energy use compared to a pre-retrofit scenario in which occupants worked without turning their lights on. Second, the control system turns off the electric lights only if the occupancy sensor does not detect occupancy for the specified timeout interval. This means slightly extended lighting hours if occupants allow the control system to turn off their lights rather than manually shutting the lights off while leaving a room. The performance penalty due to extended hours could be significant if occupants walk in and out of their offices frequently. Finally, the layout of the space requires some occupants to pass through intermediate offices to reach their offices. This unnecessarily triggers the lights in the intermediate (unoccupied) offices, which did not happen in the pre-retrofit scenario.

These issues could be addressed in part by changing to a "manual-on auto-off" system in which occupants turn their lights on manually and the control system shuts lights off automatically.

#### 6.2.2.3 Light level tuning

As discussed earlier, the post-retrofit ballasts were capped far below the installed power levels in order to maintain appropriate workplane illuminance levels. The same light output could have been achieved at lower power by installing low ballast factor ballasts, reducing the number of installed lamps, and/or adjusting fixture layout. While this did not happen due to specific considerations associated with the demonstration project, it emphasizes the importance of taking light levels into account at the beginning of a retrofit project and specifying accordingly. The installed dimmable ballasts allow users to tune the light output to higher levels in the future to accommodate changes in space usage, lamp burnouts and lumen depreciation, but at the cost of lower efficacy at lower outputs.

#### 6.2.2.4 Standby power

The control devices are on continuously, which adds to energy use. The post-retrofit standby power is typically roughly 0.04W/sq ft (over 4% of tuned LPD), which would correspond to nearly 1 Wh/sq ft/day if lights were turned off for the entire day. Low use levels exacerbate the effect of standby power, both because lights spend more time turned off (in standby mode) and because the overall EUI is very low. Standby power clearly played a significant role in contributing to post-retrofit energy use, particularly on weekends and holidays. Please note that the Hybrid ILDC system is a research prototype and is not optimized to reduce standby power. A commercial version would streamline control and communication equipment to reduce standby power and save additional energy.

### 6.2.3 Reduce carbon footprint of the lighting system

The carbon footprints for code baseline lighting energy use, pre-retrofit metered lighting energy use and post retrofit metered lighting energy use in lbs/sq ft/yr are presented in Table 12. All

values are based on an emission factor of 1.045 lb $CO_2$/ kWh. Percentage savings are also indicated in the table.

Table 12: Building 279 carbon footprint

| | | | | Percent savings compared to… | |
|---|---|---|---|---|---|
| | Pre-retrofit metered | Post-retrofit metered | Code baseline | Pre-retrofit metered | Code baseline |
| Annual $CO_2$ emissions (lbs/sq ft/yr) | 1.39 | 1.00 | 4.75 | 28% | 79% |

The goal was to demonstrate at least a 45% reduction in carbon footprint compared to a building with code baseline lighting energy in the same region. Results show that Hybrid ILDC demonstrated a 79% reduction in carbon footprint compared to the code baseline, significantly exceeding this goal. The system also reduced carbon emissions by 28% compared to the metered pre-retrofit.

### 6.2.4 Cost-effectiveness

See section 7 Cost Assessment for a detailed discussion on cost-effectives.

### 6.2.5 System reliability

The Hybrid ILDC system is carefully designed and thoroughly tested to withstand component failures. The health of key components is constantly monitored and an alarm notification is issued if any component fails to respond to query messages. Moreover, should any component fail, the rest of the system continues to support essential functions. The component failure notifications were monitored throughout the post retrofit study period but no system-wide failures were noticed. Note that there were a few incidences of power outages some caused by lightning strikes during the demonstration period. The hybrid ILDC system survived those outages. In spite of potentially hostile RF environment at the Army site, no issues related to reliability of wireless controls were observed. Thus, Hybrid ILDC exceeded the success criteria for the reliability metric.

### 6.2.6 System Maintainability

System maintainability is gauged based on the number of scheduled and unscheduled maintenance actions and corresponding downtimes. The project team maintained a log of all the maintenance actions performed during the demonstration period with appropriate annotations to describe what kinds of actions were performed, whether they were scheduled or unscheduled actions and whether there was any downtime associated with the maintenance action. Note that downtime is defined as the duration when the lighting control system is non-responsive to

manual on-off commands. There was no downtime due to Hybrid ILDC system during the demonstration period.

Hybrid ILDC is an experimental system made from COTS components. It has a touch screen Tablet in each room which acts as a user interface. These tablets run a Windows operating system which occasionally crashed. Tablets were scheduled to auto-reboot once a week. On a couple of occasions some tablets failed to boot properly after the scheduled shutdown. All the maintenance actions listed in Table 13 were due to the failure of Windows operating system running on the tablet. Since Hybrid ILDC is a research prototype, some features and functions do not reflect the product grade performance. A productized version of Hybrid ILDC will benefit from a robust platform, vigorous testing and quality control processes to ensure reliable performance.

Hybrid ILDC has in-built status monitoring feature which automatically alerted the administrator when any tablet failed to respond to ping messages. These issues were promptly resolved by simply rebooting the tablet. The system had a manual on-off switch paired with each tablet which meant the occupants can control their lights even if the tablet is down. Hence, there was no downtime associated with the tablet failure.

The objective was to show no more than 4 scheduled maintenance actions per month and no more than 8 hours of scheduled maintenance downtime per month. Additionally, system should require no more than 2 unscheduled maintenance actions per month and no more than 4 hours of unscheduled maintenance downtime per month. Results in Table 13 indicate that Hybrid ILDC met these success criteria.

Table 13: Maintenance record of Hybrid ILDC system in building 279

| Month | Scheduled Maintenance | | Unscheduled Maintenance | |
|---|---|---|---|---|
| | Actions | Downtime Hrs | Actions | Downtime Hrs |
| May | 1 | 0 | 0 | 0 |
| June | 0 | 0 | 0 | 0 |
| July | 0 | 0 | 1 | 0 |
| August | 0 | 0 | 1 | 0 |
| September | 0 | 0 | 1 | 0 |
| October | 0 | 0 | 1 | 0 |
| November | 0 | 0 | 0 | 0 |
| December | 0 | 0 | 0 | 0 |

### 6.2.7 Workplane illuminance

A goal of the new lighting control system is to improve the lighting environment by bringing light levels closer to specified targets. To quantify the illuminance changes, a photometric survey was carried out before and after the lighting control system installation. Since in this building all rooms are conference rooms, private offices, or semi-private offices, the 333-750 lux target range was used throughout.

The post retrofit survey took place on 4/13/11 between 8:00 pm and 9:00 pm, and resulted in workplane illuminance readings ranging from 314 to 491 lux. The pre and post-retrofit measurements were taken by the same person using the same light meter, at identical locations following the same methodology. Results are presented below in Figure 16. Black diamonds and written values show the median, blue rectangles extend to the first and third quartiles, and whiskers cover the entire range of the data. The red shaded area shows the range of acceptable values.

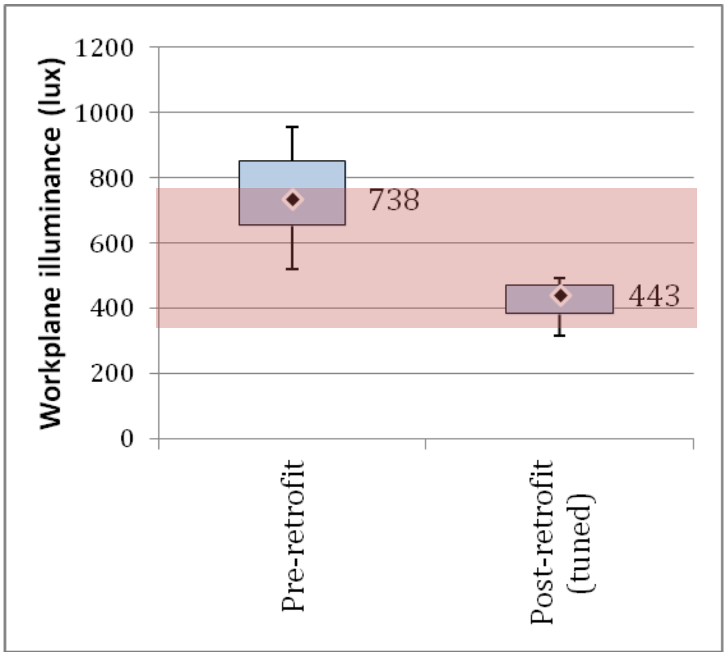



Figure 16: Pre-retrofit and post-retrofit tuned workplane illuminance levels in building 279

Pre-retrofit and post-retrofit light measurements were analyzed in terms of the average deviation from the acceptable range over the set of measurements. Fourteen of the 29 pre-retrofit measurements fell outside the range, giving the dataset an average deviation of 54 lux. All of these measurements had higher light levels than the specified range. Only one of the 29 post-retrofit measurements fell outside the acceptable range (falling below the range), giving the dataset an average deviation of 1 lux.

Table 14: Building 279 illuminance results

| Performance objective | Pre-retrofit metered | Post-retrofit metered | Percent improvement from pre-retrofit metered |
|---|---|---|---|
| Average deviation from specified illuminance range (lux) | 54 | 1 | 98% |

The objective was to show at least a 10% reduction in average deviation from the DPW requirement compared to pre-retrofit measurements. Results indicate that Hybrid ILDC successfully met this criterion. The target area was overlit during the pre-retrofit period, and the post-retrofit system brought light levels closer to the target workspace levels.

#### 6.2.8 Ease of commissioning and installation

Ease of installation and commissioning was evaluated based on feedback from the two key installation and commissioning agents. Phone interview asked installers to rate the difficulty of various tasks, agree or disagree with several statements regarding the work they performed, and provide free response comments and feedback.

Both installers rated all installation tasks a 1 (very straightforward) or a 2 (somewhat straightforward) except the following:

- One installer said fixture replacement had neutral difficulty. He explained that the hardware inside the fixtures made keeping fixtures in the same locations slightly challenging.
- One installer said the race work and molding work had neutral difficulty, largely because of a lack of direction and the disorganized state of the existing building.
- One installer said running 110V power had neutral difficulty.
- One installer said the Cat 5 cable installation was somewhat challenging.

In response to a variety of qualitative questions, installer responses included:

- Both installers were neutral, disagreed, or strongly disagreed with the statements "The project presented installation challenges that I was not familiar with" and "the installation took longer and required more effort than typical installations of a similar size".
- One was neutral and one disagreed as to whether they could have performed the installation with minimal support beyond written materials.
- Both agreed or strongly agreed that they could perform future installations of the same systems with minimal support.
- Both were neutral or agreed that written instructions were clear and comprehensive.
- In response to a question asking if they had concerns that problems could have come up during the installation process, one disagreed and one agreed, citing concerns that they only received one step of instructions at a time in that building, which prevented them from planning their work there as effectively as possible.

In free response discussion, one installer mentioned that access to the building as a key challenge. On installer mentioned that since the system is experimental there was a lot of trial and error in terms of sensor placement, but that this was not a big problem since the sensors were easy to move. One installer said he found it somewhat problematic that they only received a few parts at a time and had to perform early phases of the installation in all the rooms before they received all the hardware for the project. This meant that they could not plan out the entire installation in advance. He said it went pretty smoothly despite this but that in future installations it would be helpful to have all the relevant information before starting work.

Although the installers found the Hybrid ILDC system installation the most difficult of the three installations, Hybrid ILDC did not appear to present major installation challenges. While installer feedback suggests that the commercial product will need a streamlined process and set of instructions, it appears that with these changes the system will be reasonably straightforward to install.

6.2.9 User satisfaction

DPW was only able to identify four occupants for the user satisfaction survey in building 279 during both the pre-retrofit and post-retrofit study periods. Out of 4 occupants who were sent the questionnaires, one person responded to the survey during the pre-retrofit period, and two responded during the post-retrofit period. The extremely low number of people surveyed limited the extent to which results can be considered representative. It is not possible to say if occupant satisfaction improved overall; however, some insight still emerged from the responses.

In general, all occupants who responded appeared content with their office lighting and controls during both study periods. All three respondents said they found their lighting comfortable and said they were satisfied with their ability to control their lights.

Occupants appeared less content with shade control during both study periods. The pre-retrofit respondent disagreed with the statement “I am satisfied with my ability to control my window shades or blinds”; one post-retrofit occupant agreed and one disagreed with the same statement. One post-retrofit occupant commented that the blinds move up and down frequently, and saw this as a problem. It is possible that either the blinds are moving too frequently or that the intent of the blind control was not adequately explained to this occupant.

6.2.10 System Integration

To study the effects of the Hybrid ILDC system on HVAC energy consumption, a detailed simulation model of building 279 was developed in EnergyPlus and lighting control strategies were modeled in Matlab. A rendering of the EnergyPlus model of building 279 is shown in Figure 17 with the relevant rooms of interest circled.

Figure 17: Rendering of EnergyPlus model of building 279

The EnergyPlus model was developed from available engineering drawings and specifications and from data supplied by building management during a site survey. Data pertaining to geometry, loads, profiles, HVAC equipment and control strategies were surveyed and used to develop inputs for the simulation model. Although the whole building was modeled, particular

attention was given to the nine relevant rooms of interest where the Hybrid ILDC is installed, including characterization of the transmittance of each window, installed lighting and blinds, locations of daylight sensors, etc. However, because of complexities associated with modeling simultaneously operating fan coil units and terminal box window A/C units, it was decided to model the HVAC systems as ideal loads or purchased air. This was an objective way to evaluate HVAC energy consumption without needing specific HVAC implementation details.

The control strategies for the Hybrid ILDC were implemented in Matlab. BCVTB was used as a simulation platform which enables the co-simulation of EnergyPlus and Matlab. Because occupancy is one of the most important drivers of energy consumption, and critical to assessing the performance of occupancy-based controls, significant efforts were spent to develop a dynamic occupancy model for building 279 based on collected data. Occupancy data collected from occupancy sensors for 41 weekdays and 9 weekend days from the period 5/4/2011 to 7/2/2011 were used to create an occupancy model to drive the simulations. Comparisons between the sensor recorded occupancy and model predicted occupancy are shown in Figure 18 and Figure 19.

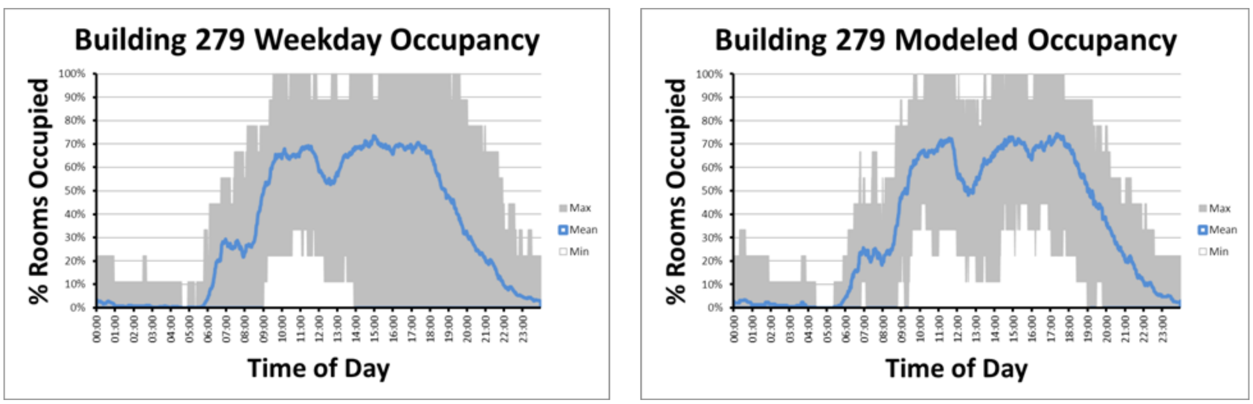



Figure 18: Recorded weekday occupancy (left) versus modeled weekday occupancy (right) in building 279

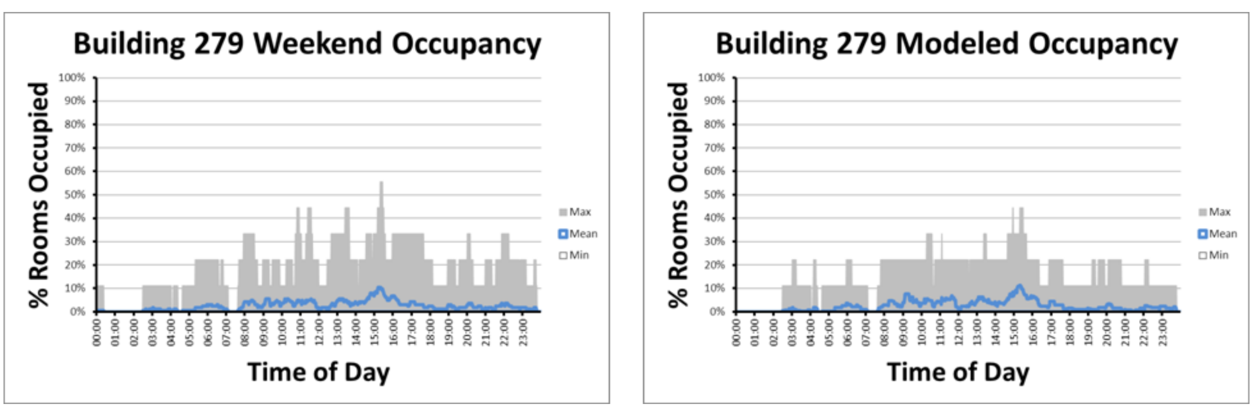



Figure 19: Recorded weekend occupancy (left) and modeled weekend occupancy (right) in building 279

To evaluate the System Integration performance objective, the simulated performance of the Hybrid ILDC system was compared against the simulated performance of code baseline. Because of uncertainties in modeling the pre-retrofit blinds for the code baseline, three code baseline cases were used:

- Horizontal blinds, open, with reflectance 30%.
- Vertical blinds, open, with reflectance 30%.
- Horizontal blinds, open, with reflectance 80%.

Full year simulations in one minute time steps were run using Typical Meteorological Year 3 weather data for Barstow Daggett (nearest location for which weather data is available). The simulation results are shown in Figure 20 and summarized in Table 15. For this location, climate and zone orientation, HVAC energy consumption is primarily cooling.

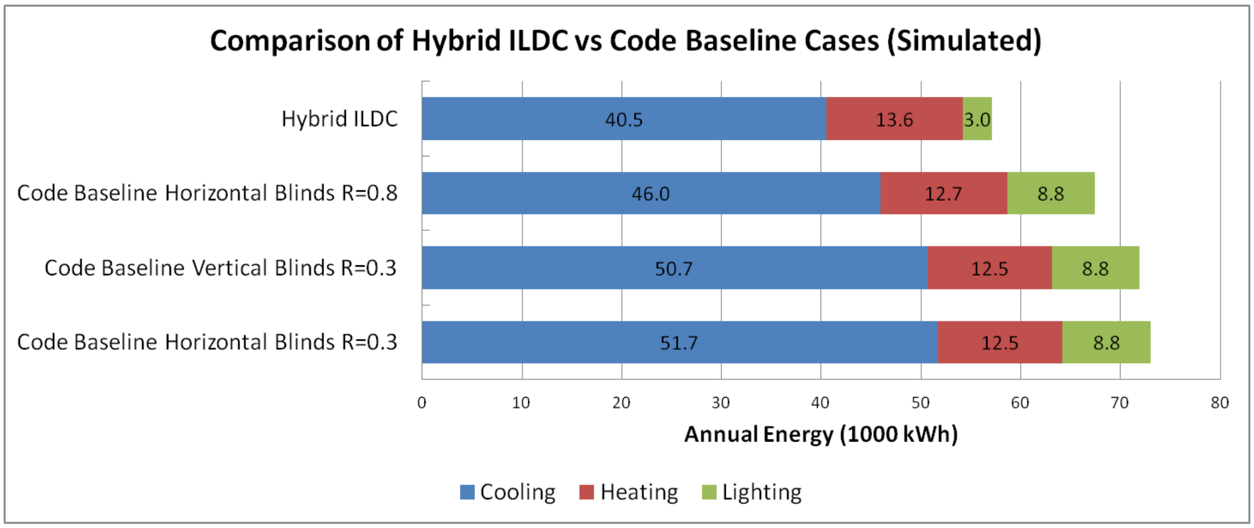



Figure 20: Comparison of Hybrid ILDC versus code baseline in building 279 (simulated)

Table 15: Annual energy savings due to Hybrid ILDC over code baseline in building 279 by subcategory (simulated)

| | Lighting savings | Cooling savings | Heating savings | HVAC savings |
|---|---|---|---|---|
| Code baseline horizontal blinds R=0.3 | 66.2% | 21.5% | -8.7% | 15.6% |
| Code baseline vertical blinds R=0.3 | 66.2% | 20.0% | -9.3% | 14.2% |
| Code baseline horizontal blinds R=0.8 | 66.2% | 11.8% | -7.4% | 7.7% |

The results with respect to the system integration performance objective for Hybrid ILDC in building 279 are shown in Table 16. The success criterion was to show greater than 5% savings in HVAC energy consumption compared with code baseline HVAC energy consumption. Clearly, the Hybrid ILDC system exceeded the performance target even under the conservative assumption of R=0.8.

Table 16: Hybrid ILDC system integration results

| Performance objective | Code baseline HVAC energy consumption (1000 kWh/year) | Hybrid ILDC HVAC energy consumption (1000 kWh/year) | % HVAC savings |
|---|---|---|---|
| System Integration | 58.7 – 64.2 | 54.1 | 7.7% – 15.6% |

## 6.3 PERFORMANCE OF OCCUSWITCH IN BUILDING 602

To analyze the energy and demand performance of the OccuSwitch system installed in Building 602, a total of four discrete data sets were examined. The time intervals for the different test periods, the total number of days analyzed and the number of weekdays, weekends and holidays is given in Table 17.

Table 17: Number of days analyzed during pre-retrofit and post-retrofit periods

| | *Number of Days Analyzed Over Course of Testing in Building 602* | | | | | |
|---|---|---|---|---|---|---|
| Test Period | Start | Stop | Total Days | Weekdays | Weekend Days | Holidays |
| Pre-retrofit | 9/16/2010 | 1/7/2011 | 71 | 44 | 21 | 6 |
| Post-retrofit 1 | 5/7/2011 | 12/23/2011 | 120 | 83 | 33 | 4 |
| Post-retrofit 2 | 1/3/2012 | 7/15/2012 | 176 | 123 | 49 | 4 |
| OccuSwitch Rev | 7/27/2012 | 9/26/2012 | 62 | 43 | 18 | 1 |

The post-retrofit period 1 dataset used in analysis consists of 120 days made up of 83 weekdays, 33 weekend days, and 4 holidays that were recorded from May to December 2011. This dataset included fewer days than the targeted six months of post-retrofit data due to a hardware failure caused by a lightning storm that could not be quickly resolved because of visitation restrictions. However, since seasonal trending associated with daylight availability did not appear to be a factor in this building, this dataset is believed to be sufficient for robust annual energy use estimates.

The post-retrofit period 2 dataset ran from Jan 2012 until July 25, 2012. Note that OccuSwitch firmware was upgraded on July 26, 2012 to fix some of the issues observed earlier in the demonstration. The final test period, Post OccuSwitch Revision period, was used to estimate any changes in system performance caused by the firmware upgrade.

The following sections present results comparing the pre-retrofit and the post-retrofit 1 study periods. Further energy analyses that include the post-retrofit period 2 and 3 datasets can be found in Appendix 1 (p. 121).

### 6.3.1 Reduce lighting demand

Peak LPD was calculated for each week of data collected. No outliers were identified for either the pre-retrofit or the post-retrofit data. These datasets included a peak pre-retrofit metered LPD of 1.14 W/sq ft and a peak adjusted pre-retrofit LPD of 1.17 W/sq ft. The peak post-retrofit LPD

over a 15 minute interval is 0.96 W/sq ft, a 16% reduction compared to the pre-retrofit metered, an 18% reduction compared to the adjusted pre-retrofit and a 47% reduction compared to code baseline. The post-retrofit system reduced peak LPD by 4% compared to the level associated with the 2007 reference code (1.00 W/sq ft).

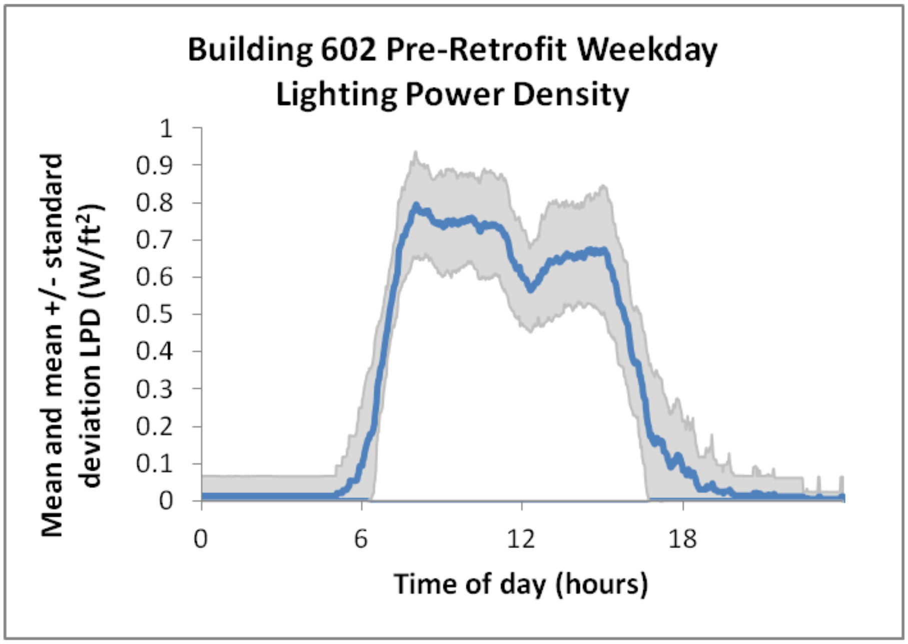



Figure 21: Pre-retrofit metered LPD in building 602

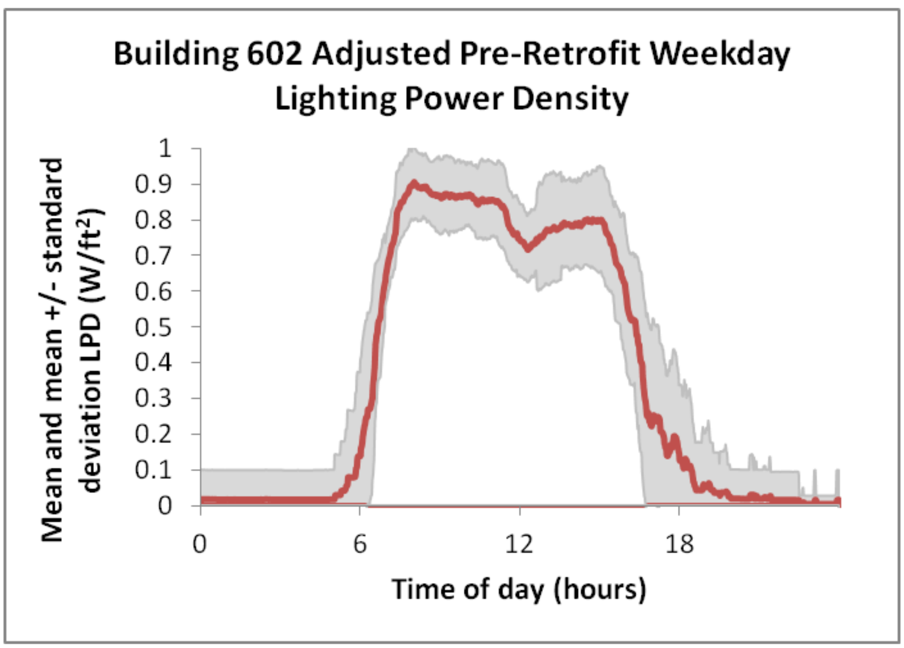



Figure 22: Adjusted pre-retrofit LPD in building 602

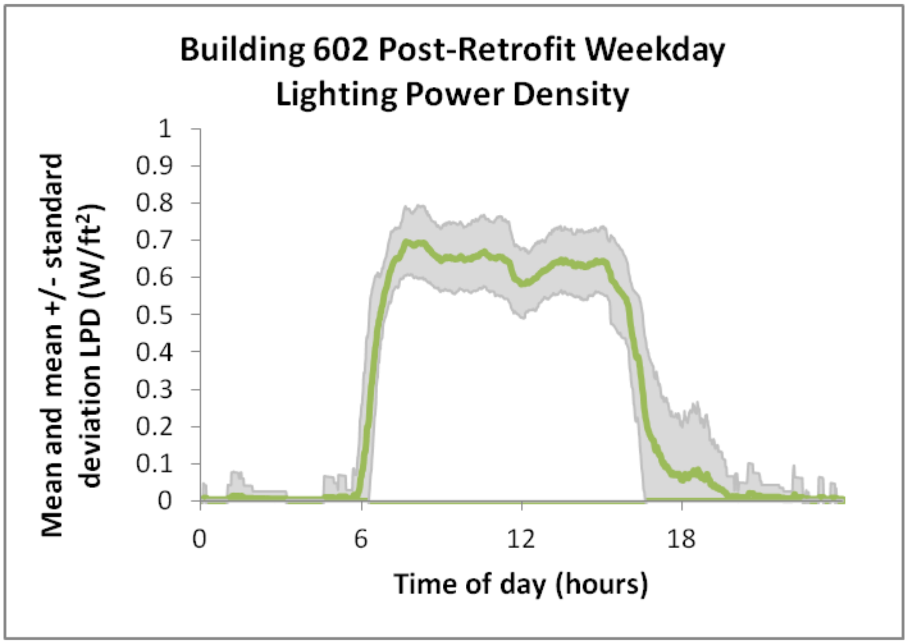



Figure 23: Post-retrofit metered LPD in building 602

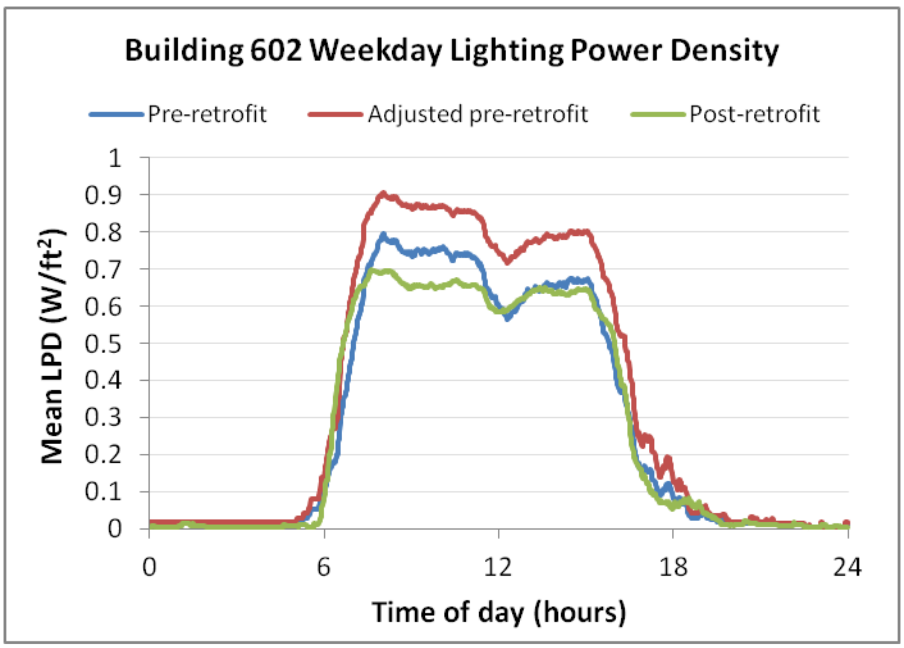



Figure 24: Mean weekday LPD for the pre-retrofit (blue), adjusted pre-retrofit (red), and post-retrofit (green) in building 602

The goal was to demonstrate at least a 25% reduction in peak LPD compared to code baseline. The results show 47% savings compared to the code baseline, substantially exceeding the target.

Mean weekday LPDs over the course of the day are shown in Figure 24 for the pre-retrofit and post-retrofit study periods. The plots show that use patterns for the building as a whole remained

approximately the same during the two measurement periods. Peak mean LPD is lower in the post-retrofit period, especially compared to the adjusted pre-retrofit.

Table 18: Building 602 peak LPD results

| | | | | | Percent savings compared to… | | |
|---|---|---|---|---|---|---|---|
| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline | Post-retrofit metered | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
| Peak LPD over a 15 minute period (W/sq ft) | 1.14 | 1.17 | 1.81 | 0.96 | 16% | 18% | 47% |

In all three cases, mean LPDs stay well below the installed values of 1.49 W/sq ft for the pre-retrofit and 1.46 W/sq ft for the adjusted pre-retrofit and post-retrofit system. In fact, mean post-retrofit LPD stays below 50% of the installed LPD for most of the day. The low pre-retrofit operating LPD indicates that at a given time, lights are likely to be turned off in several areas of the building. The post-retrofit control system lowered the operating LPD even further. Similarity in overall energy use patterns hides the fact that the retrofit shifted power density from the perimeter areas to the open office area due to lamp shifting. This will be discussed in more detail below.

### 6.3.2 Reduce electrical energy consumption for lighting

Table 19: Building 602 EUI results

| | | | | | Percent savings compared to… | | |
|---|---|---|---|---|---|---|---|
| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline | Post-retrofit metered | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
| Weekday energy use intensity (Wh/sq ft/day) | 7.01 | 8.59 | 18.1 | 6.71 | 4.3% | 22.0% | 62.9% |
| Weekend energy use intensity (Wh/sq ft/day) | 0.18 | 0.25 | 0 | 0.37 | -105.6% | -48.0% | N/A |
| Holiday energy use intensity (Wh/sq ft/day) | 3.36 | 4.72 | 0 | 1.38 | 58.9% | 70.8% | N/A |
| Annual energy use intensity (kWh/sq ft/yr) | 1.81 | 2.23 | 4.54 | 1.74 | 4.2% | 22.2% | 61.8% |

Daily and annual energy results are presented below in Table 19. Annual EUI is calculated from average daily EUIs based on an assumed distribution of 251 weekdays, 104 weekend days, and 10 holidays per year.

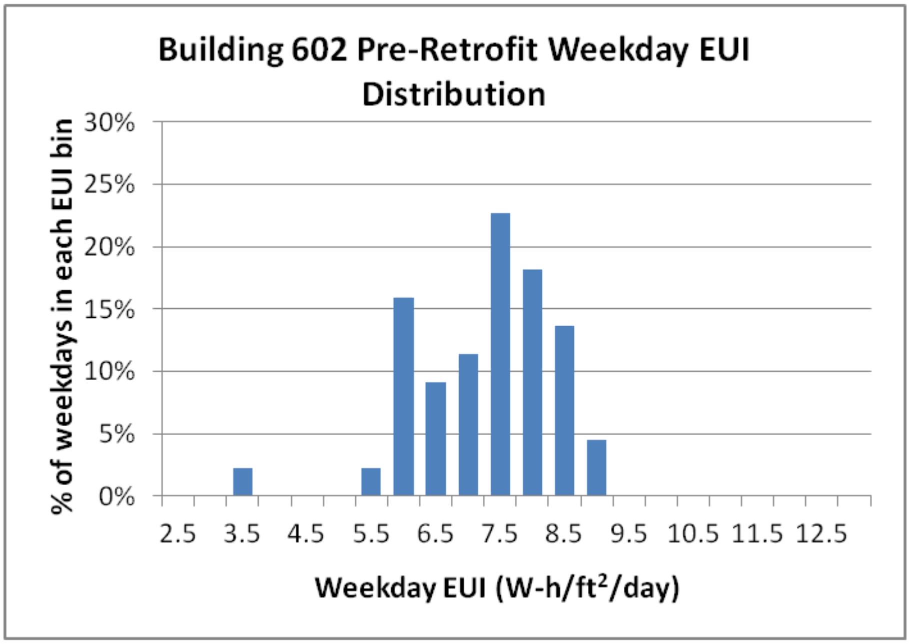



Figure 25: Pre-retrofit weekday EUI in building 602

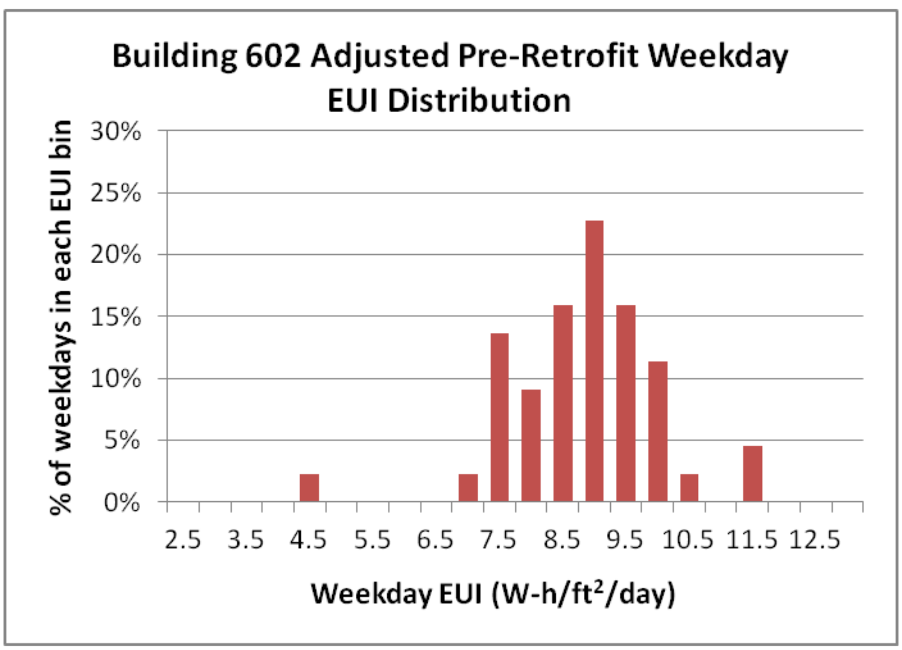



Figure 26: Adjusted pre-retrofit weekday EUI in building 602

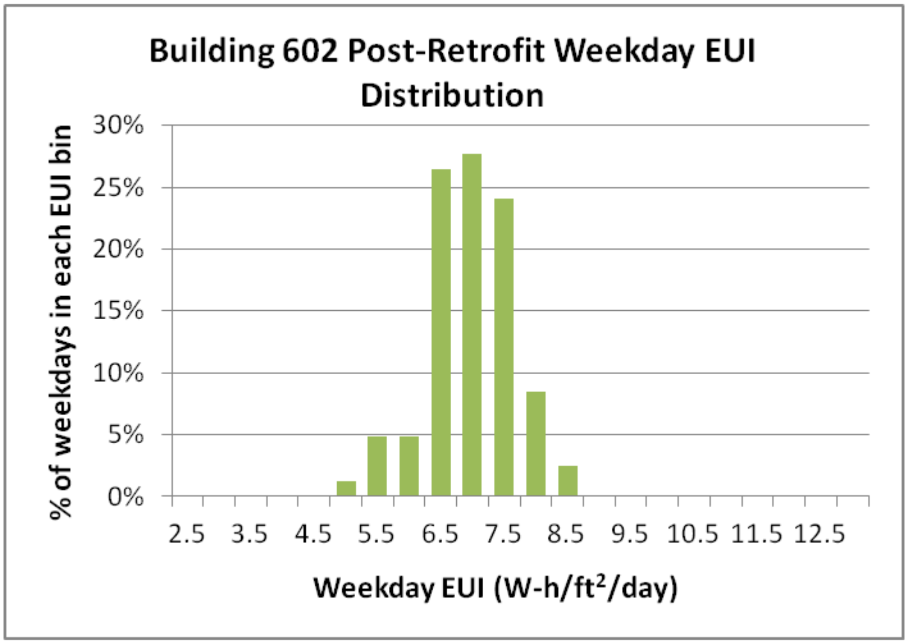



Figure 27: Post-retrofit weekday EUI in building 602

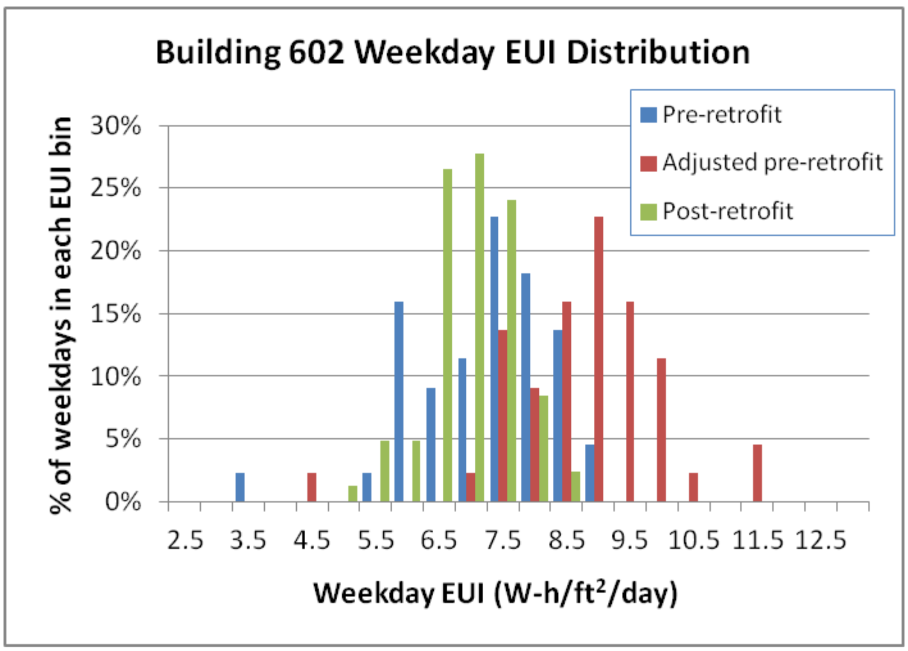



Figure 28: Distribution of weekday EUIs for the metered pre-retrofit (blue), the adjusted pre-retrofit (red), and the metered post-retrofit scenario (green) in building 602

Analysis of the post-retrofit dataset for the building as a whole shows an average weekday EUI of 6.71 Wh/sq ft/day, weekend EUI of 0.37 Wh/sq ft/day, and holiday EUI of 1.38 Wh/sq ft/day. As shown in Table 19, this results in an annual EUI of 1.74 kWh/sq. ft/yr, corresponding to 62% annual energy savings compared to the code baseline, 22% annual savings compared to the adjusted pre-retrofit, and 4% annual savings compared to the metered pre-retrofit. The post-retrofit system also uses 31% less energy than the 2007 code reference.

The goal was to demonstrate at least a 45% reduction in EUI compared to the code baseline lighting EUI. The results demonstrated 62% savings over the code baseline, significantly exceeding the target.

The distribution of weekday EUIs for the pre-retrofit, adjusted pre-retrofit and post-retrofit scenarios are shown below in Figure 28. Each column shows the percentage of metered weekday EUIs that fall into the EUI range ending in the listed value. The system decreased weekday energy use by 4% compared to the pre-retrofit and by 22% compared to the adjusted pre-retrofit. At the same time, weekend energy use increased and holiday energy use decreased. Overall, weekday energy use made the dominant contribution to annual energy use during both study periods.

6.3.2.1 Breakdown of energy consumption by space type

Analyzing the results by space types gives more insights into system performance. The installation area in building 602 was served by eight individually metered lighting branch circuits. Table 20 summarizes the different spaces that were monitored, the control strategies that were tested, and details the lighting equipment and lighting power densities for the situation prior to the retrofit (pre-retrofit) and the situation after the controls were installed and commissioned (post-retrofit).

Table 20: Summary of pre-retrofit and post-retrofit lighting systems in building 602

| Space Description | Area (sf) | Pre-retrofit | | | Post-retrofit | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | # of fixtures | # of lamps | Original LPD (W/sf) | # of fixtures | # of lamps | Installed LPD (W/sf) | # of multi-sensors | Lighting Control Strategies Tested |
| Three perimeter private offices, SE | 356 | 9 | 29 | 0.40 | 9 | 18 | 0.58 | 3 | Occupancy sensing, Delighting |
| Three perimeter private offices, SW | 375 | 9 | 24 | 0.48 | 9 | 18 | 0.61 | 3 | Occupancy sensing, Delighting |
| Two perimeter open offices, SW | 390 | 11 | 28 | 0.44 | 11 | 68 | 0.52 | 2 | Occupancy sensing, Delighting |
| Five perimeter private offices, NE | 652 | 15 | 25 | 0.70 | 15 | 2 | 0.64 | 5 | Occupancy sensing, Delighting |
| Two perimeter private offices and conference room, N | 608 | 15 | 48 | 0.41 | 15 | 30 | 0.60 | 3 | Occupancy sensing, Delighting |
| Core open office – Center | 533 | 10 | 10 | 1.26 | 10 | 20 | 0.78 | 2 | Occupancy sensing |
| Core open office – West | 711 | 14 | 9 | 1.63 | 14 | 28 | 0.75 | 5 | Occupancy sensing |
| Core open office - East | 750 | 12 | 16 | 1.19 | 12 | 24 | 0.92 | 4 | Occupancy sensing |
| **Overall** | **4,375** | **101** | **201** | **1.27** | **101** | **202** | **1.24** | 27 | |

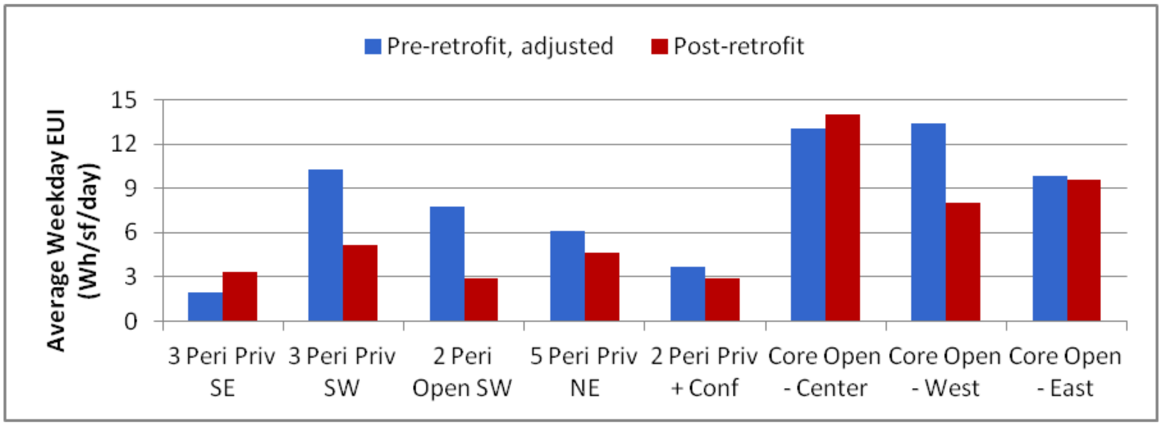



Figure 29: Average weekday EUI for five metered zones.

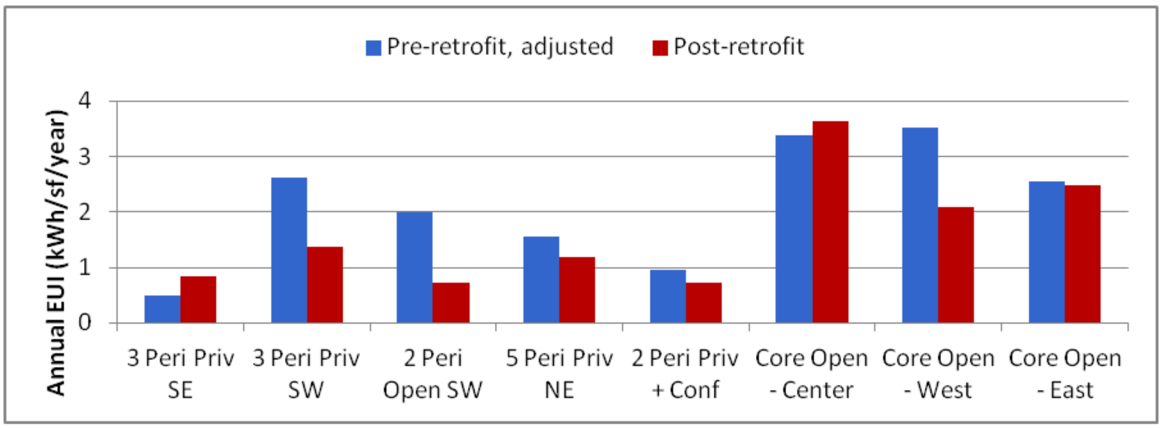



Figure 30: Projected annual lighting EUI for each of the five metered zones

The adjusted pre-retrofit and post-retrofit metered average weekday lighting EUI is plotted in Figure 29. The pre and post-retrofit measurements were used to project the annual lighting energy use (Figure 30) and the annual lighting energy savings (Figure 31) for each of the eight measured zones.

Significant energy savings were measured during the post retrofit period in the five perimeter private and open offices in the southwest section of the building as well as the core open office area in the west section of the site. Projected annual energy use was decreased by approximately 1.25 kWh/sf/year in the southwest perimeter areas which translates into energy savings of 48 – 63%. Also, 41% energy savings was obtained in the western core open office area resulting in an annual decrease of 1.4 kWh/sf/yr.

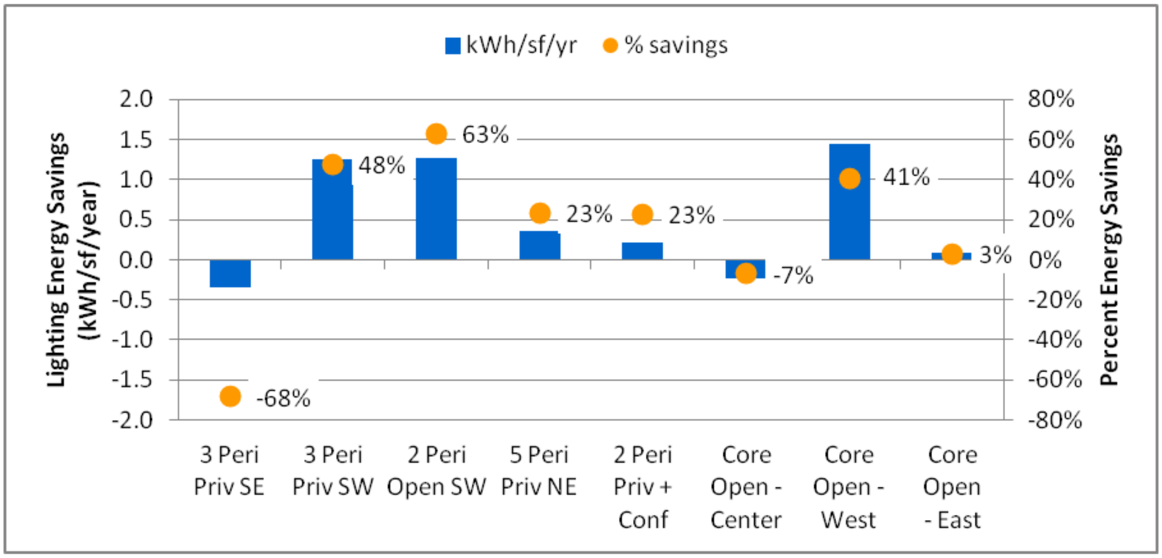



Figure 31: Projected annual lighting energy savings (left scale) and percent energy savings (right scale). Savings are calculated using the adjusted pre-retrofit

Several factors merit additional discussion:

6.3.2.2 Interior open office vs. perimeter areas

The adjusted pre-retrofit accounts for changes in lamp distribution during the retrofit and isolates the impact of the lighting controls, as discussed earlier. This is particularly important because the open office areas tend to have much longer operating hours than the private offices. Comparison with the adjusted pre-retrofit isolates energy savings due to the combination of control strategies implemented (e.g. occupancy sensing, daylight harvesting, and personal controls).

Given the variation in use patterns and daylight availability between the perimeter areas and the central open office areas, it is helpful to evaluate these areas separately. The adjusted pre-retrofit makes this comparison meaningful by eliminating the effect of lamp shifting.

The installed lighting controls reduced annual energy use by 34% in the perimeter areas and 15% in the central open office space compared to the adjusted pre-retrofit. This shows that the control system is saving a significant percentage of total building energy, but also that controls in the open office are not as effective as controls in perimeter areas. This discrepancy is in part due to factors discussed below.

6.3.2.3 Open office zones

First, the open office is divided into three zones, each corresponding to a lighting branch circuit. As operated, each zone typically turns on in the morning when the first cubicle becomes occupied and turns off in the evening when all the cubicles are unoccupied, staying on throughout the day. This means that occupancy sensing is not saving much energy in the open office during work hours. Breaking the area into smaller zones would likely increase open office occupancy savings.

The OccuSwitch system is intended to use existing circuitry, thereby keeping installation costs low. This means that barring a more invasive installation process, existing circuit layout dictates the configuration of control zones. In this building, the open office could not have been broken into additional zones without a more intensive retrofit that included modifying lighting branch circuits. However, the same type of retrofit could potentially achieve deeper savings in offices with smaller branch circuit areas.

#### 6.3.2.4 Open office occupancy sensors

Second, it appears that occupants in corridors and transition areas may be triggering open office occupancy sensors and keeping lights on in unoccupied areas. In particular, energy use in the open office zone that includes the main building entrance increased relative to the adjusted pre-retrofit, while energy use in other two zones decreased. This suggests that occupants walking to and from the entrance sometimes trigger occupancy sensors to turn on the lights in the unoccupied zone. This could be addressed by making corridor areas a separate zone and shielding occupancy sensors to prevent unnecessary triggers. As noted above, making corridors separate zones was not possible in this site without a more invasive retrofit that included modifying lighting branch circuits.

#### 6.3.2.5 Higher savings in private offices

Private offices in building 602 have small 3'4" by 2' windows which admit some daylight enabling daylight linked dimming. As opposed to auto-on strategy implemented in open office areas, the OccuSwitch systems in private offices were configured with manual-on auto-off control regime. Manual-on prevents inadvertent light turn-on due to motion (e.g. in nearby hallways and corridors) thereby preventing energy wastage. Since many private offices are intermittently occupied, vacancy sensing has more opportunities to save energy by turning lights off when room is unoccupied compared to the open office zones (inhabited by multiple occupants). All these factors contributed to higher savings in private offices compared to open plan offices.

### 6.3.3 Reduce carbon footprint of the lighting system

The carbon footprint of the pre-retrofit metered, adjusted pre-retrofit, code baseline, and post-retrofit lighting system are presented in Table 21. All values are derived based on an emission factor of 1.045 lb $CO_2$/kWh.

Table 21: Building 602 carbon footprint

| | | | | | Percent savings compared to… | | |
|---|---|---|---|---|---|---|---|
| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline | Post-retrofit metered | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
| Annual $CO_2$ emissions (lbs/sq ft/yr) | 1.89 | 2.33 | 4.75 | 1.81 | 4% | 22% | 62% |

The goal was to demonstrate at least a 45% reduction in carbon footprint compared to a building with code baseline lighting energy in the same region. Results show that OccuSwitch achieved a 62% reduction in carbon footprint compared to the code baseline lighting energy use, meeting this goal. It also reduced carbon emissions by 4% compared to the pre-retrofit and 22% compared to the adjusted pre-retrofit.

### 6.3.4 Cost-effectiveness

See section 7 Cost Assessment for a detailed discussion on cost-effectives.

### 6.3.5 System reliability

OccuSwitch is a room based lighting control system. To gauge its reliability, the project team relied on occupants and the building manager to report any issues. No system-wide failures were reported during the demonstration period. In spite of potentially hostile RF environment at the Army site, no issues related to reliability of wireless controls were observed. Thus, it exceeded the success criteria for the reliability metric. Several other issues unrelated to the OccuSwitch system were found which are discussed in the next subsection.

### 6.3.6 System Maintainability

In building 602 the OccuSwitch system had performed as per intent; however, there had been a few scheduled and unscheduled maintenance issues. The contractor did not follow the wiring instructions which lead to wiring errors. Scheduled maintenance action was performed to correct the erroneous wiring. Re-wiring was done at night, therefore no downtime was experienced by the occupants.

Soon after the retrofit, the building manager reported a perceived delay in turning lights on in the restroom. This issue was resolved by replacing the programmed start ballasts in the restroom with instant start ballasts, which reduced the delay but sacrificed dimming capabilities in the restrooms. The building manager was satisfied with the response time after the replacement.

Another issue encountered in building 602 was caused by malfunctioning amplifiers. Amplifiers are not part of OccuSwitch system however, 3 third party amplifiers were installed in the open plan office area to extend the range of dimming signals to support a large number of fixtures. Although the OccuSwitch system was operating properly, malfunctioning amplifiers prevented it from dimming some of the lights in open plan area. Unscheduled maintenance actions were performed to replace malfunctioning amplifiers. Since then lights are working as intended and the building manager is satisfied with the operation.

The objective was to show no more than 4 scheduled maintenance actions per month and no more than 8 hours of scheduled maintenance downtime per month. Additionally, system should require no more than 2 unscheduled maintenance actions per month and no more than 4 hours of unscheduled maintenance downtime per month. Results in Table 22 indicate that OccuSwitch met these success criteria.

Table 22: Maintenance record of OccuSwitch system in building 602

| Month | Scheduled Maintenance | | Unscheduled Maintenance | |
|---|---|---|---|---|
| | Actions | Downtime Hrs | Actions | Downtime Hrs |
| May | 0 | 0 | 0 | 0 |
| June | 2 | 0 | 0 | 0 |
| July | 0 | 0 | 1 | 0 |
| August | 0 | 0 | 0 | 0 |
| September | 0 | 0 | 1 | 0 |
| October | 0 | 0 | 1 | 0 |
| November | 0 | 0 | 1 | 0 |
| December | 0 | 0 | 1 | 0 |

#### 6.3.7 Workplane illuminance

The post-retrofit survey took place on June 29, 2011 between 9:30 pm and 11:30 pm, and resulted in illuminance readings ranging from 83 to 601 lux. Of the 37 pre-retrofit measurements, measurements that were taken at different locations before and after the retrofit and measurements missing from the post-retrofit dataset were excluded, as were measurements taken in the bathrooms and break room. This left 14 data points in the perimeter offices and conference room and 12 data points in the open office area. Unfortunately, many measurements (including all of the open office measurements) were taken at floor level rather than desk level; these were taken at the same location pre-retrofit and post-retrofit and were included nonetheless. Results are presented below in Figure 32. Black diamonds and written values show the median, blue rectangles extend to the first and third quartiles, and whiskers cover the entire range of the data. The red shaded area shows the range of acceptable values.

Pre-retrofit and post-retrofit light measurements were analyzed in terms of the average deviation from the acceptable range over the set of measurements. In the perimeter private offices and conference room, 6 of the 14 pre-retrofit measurements and 6 of the 14 post-retrofit measurements fell outside the specified range, giving the datasets average deviations of 188 lux and 26 lux, respectively. In the perimeter private offices and conference room, the majority of pre-retrofit measurements outside the range were too bright, while all of the outlying post-retrofit measurements fell below the target range. In the open office, 11 of the 12 pre-retrofit measurements and 8 of the 12 post-retrofit measurements fell below the target range, resulting in average deviations of 99 lux and 56 lux, respectively. Overall, the pre-retrofit measurements deviated from target ranges by 147 lux on average, while the post-retrofit measurements deviated by an average of 40 lux.

The objective was to show at least a 10% reduction in average deviation from the DPW requirement over the average deviations prior to upgrade. Results indicate that the retrofit successfully met this criterion.

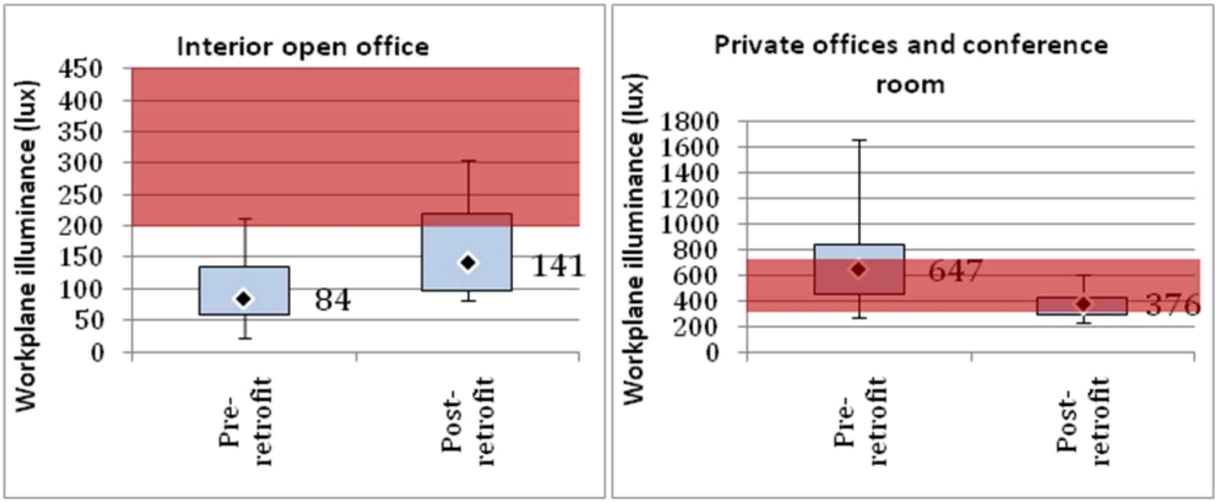



Figure 32: Pre-retrofit and post-retrofit illuminance levels in building 602

Table 23: Building 602 illuminance results

| Performance objective | Pre-retrofit | Post-retrofit | Percent improvement from pre-retrofit |
|---|---|---|---|
| Average deviation from specified illuminance range in open office (lux) | 99 | 56 | 44% |
| Average deviation from specified illuminance range in private offices and conference rooms (lux) | 188 | 26 | 86% |

In general, the post-retrofit system decreased light levels in the perimeter spaces and increased light levels in the open office. However, the majority of open office light levels still remained below the target range. This is in part due to readings taken on the floor rather than at desk level, which makes comparison to workplane illuminance targets difficult.

In both space types, the post-retrofit light levels are marginally closer to target ranges and overall deviations from the ranges are reduced. Extremely high pre-retrofit light levels in some perimeter spaces have been corrected. Since dimmable ballasts were a key part of the retrofit, light levels could be adjusted in the future in accordance with DPW requirements and/or occupant preferences.

### 6.3.8 Ease of commissioning and installation

The installers found the OccuSwitch installation the simplest of the three installations. Both installers rated all installation tasks as very straightforward, with the exception of one installer who said that putting in the power booster/amplifier on the open office circuits was somewhat challenging. Both installers commented that the project was easy, and one mentioned that components were user friendly and straightforward. One installer mentioned that the most

challenging task was working with the existing wiring due to lack of accessibility and lack of room.

In response to a variety of qualitative questions, installer responses included:

- Both installers strongly disagreed with the statements "The project presented installation challenges that I was not familiar with" and "the installation took longer and required more effort than typical installations of a similar size".
- One was neutral and one agreed that they could have performed the installation with minimal support beyond written materials.
- One agreed and one strongly agreed that they could perform future installations of the same systems with minimal support.
- Both were neutral or agreed that written instructions were clear and comprehensive.
- Both strongly disagreed with a question asking if they had concerns that problems could have come up during the installation process.

In general, both installers found the system easy to understand and install. While one installer found the building difficult to work in and mentioned that additional advanced planning and assessment of existing conditions would have helped the project, both appeared extremely comfortable with installation.

It is worth noting that despite the installers' sense of comfort with the project, a wiring mistake led to performance issues discussed above (in section 6.3.6) and had to be corrected after the initial installation. This highlights the importance of clearly communicating installation instructions and verifying that a system is installed correctly before completing a retrofit.

#### 6.3.9 User satisfaction

Ten out of 24 occupants responded to the pre-retrofit survey, and 13 out of 20 responded to the post-retrofit survey. This gave this building the most extensive survey results out of 3 buildings surveys. Key findings are:

- In both the pre-retrofit and post-retrofit surveys, about half the respondents said they found their lighting comfortable.

- None of the pre-retrofit occupants were satisfied with their ability to control their lighting, while 4 of 13 post-retrofit occupants were satisfied. This suggests that while the retrofit improved occupants' lighting controls experience somewhat, it still left plenty of room for improvement.

- Several post-retrofit free response comments from open office occupants expressed frustration with the open office lights being too bright, lack of ability to dim the lights, and inconsistent system operation. However, the survey took place during a period of time when the system was malfunctioning and there was no dimming control in the open office. This makes it difficult to separate out the effect of the malfunction with occupants' overall perceptions.

- In both pre- and post-retrofit surveys, the most common desired improvements listed were:
  - Fixtures that emit less light
  - To change the color appearance of the lighting fixtures
  - To have the ability to control the light output of the overhead light fixtures
  - Better access to windows and daylight

The survey took place during a period of time when dimming control was not working in the open office, and it is difficult to say how many comments can be attributed to this issue. It is worth noting that one error of this type can potentially erode long-term occupant confidence in a lighting control system. ***This highlights the importance of making sure everything is correctly installed and explaining how the system is intended to work to occupants early on.***

In general, occupants in this building seem to prefer very low workspace light levels. Since the retrofit increased open office light levels somewhat in accordance with DPW's preferences, this may have caused some dissatisfaction. Feedback suggesting that occupants would prefer lower light levels is a strong argument in favor of lighting controls that make it easy for occupants to control light levels, since these will potentially improve occupant satisfaction while reducing energy use.

Finally, in the OccuSwitch system demonstrated in building 602, the user selected dimming levels reset to default levels each time the space becomes unoccupied. Based on the feedback from occupants, Philips developed a software upgrade that stores the user preferred dimming level as the new defaults, thereby setting the lights to the most recent selected level the next time a space is occupied. This updated firmware was installed on July 26, 2012. This is expected to improve occupant satisfaction considerably by giving occupants lasting control over workspace light levels. Occupant responses also indicate that this may save additional energy. Given that the OccuSwitch system demonstrated in building 602 was an engineering prototype meant for testing, the issues identified during the demonstration has helped fine-tune the product for commercial release.

#### 6.3.10 System Integration

To study the effects of the OccuSwitch system on HVAC energy consumption, the DoE small office reference model post-1980 construction (V1.3_5.0 migrated to EnergyPlus V7.0) for climate zone 3B was used. This model represents a rectangular single-floor (511m$^2$) office building with core and perimeter zoning and attic space. A perspective view from the top is shown in Figure 33.

To analyze the system integration objective, the small office reference model was modified to represent the code baseline lighting energy use. Then, the lighting power in the model was modified such that the annual lighting energy savings over the code baseline was the same as the post-retrofit savings over the code baseline. In this case, the analysis is based on the annual EUI savings due to OccuSwitch over the code baseline (62%).

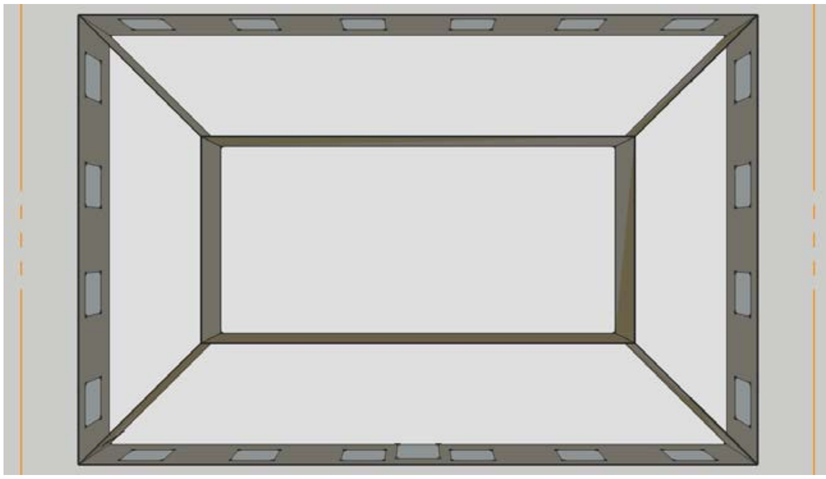


Figure 33: Top perspective view of DoE small office reference model

Simulations were run in EnergyPlus. Results are shown in Figure 34 and summarized in Table 24.

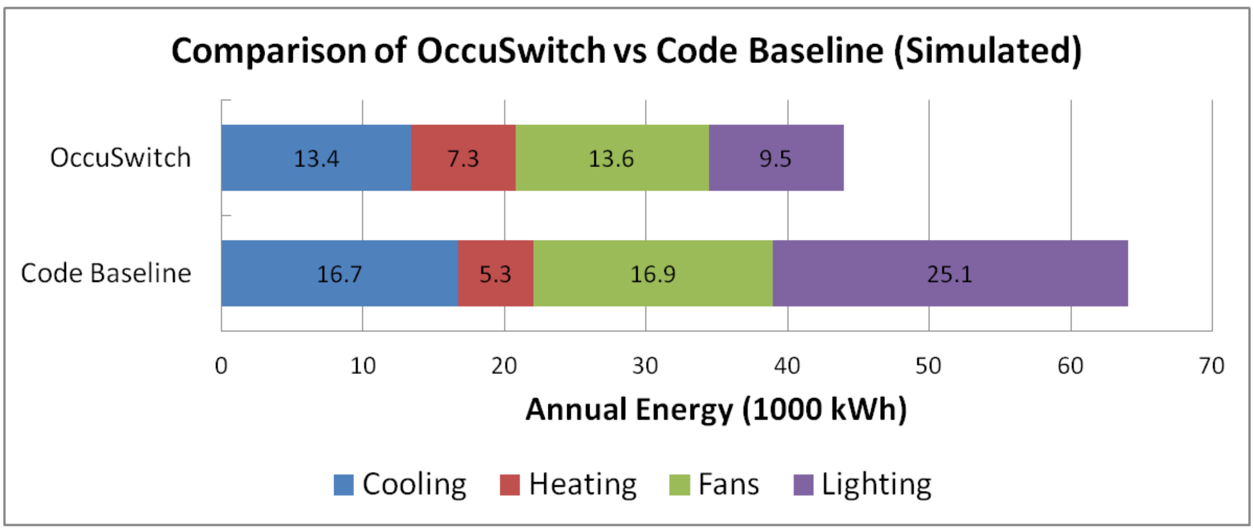



Figure 34: Comparison of OccuSwitch performance over the code baseline (simulated)

Table 24: Annual energy savings due to OccuSwitch over the code baseline by subcategory (simulated)

| | Lighting | Cooling | Heating | Fans | HVAC |
|---|---|---|---|---|---|
| Percent annual savings due to OccuSwitch over code baseline | 62.0% | 19.7% | -38.1% | 19.3% | 11.6% |

The results with respect to the system integration performance objective for OccuSwitch system are shown in Table 25. The success criterion was to show greater than 5% savings in HVAC

energy consumption compared with code baseline HVAC energy consumption. Clearly, the simulated OccuSwitch system exceeded the performance target.

Table 25: OccuSwitch system integration results

| Performance objective | Code baseline HVAC energy consumption (1000 kWh/year) | OccuSwitch HVAC energy consumption (1000 kWh/year) | % HVAC savings |
|---|---|---|---|
| System Integration | 38.9 | 34.4 | 11.6% |

## 6.4 PERFORMANCE OF DYNALITE SYSTEM IN BUILDING 988

To analyze the energy and demand performance of the Dynalite system installed in Building 988, a total of three discrete data sets were examined. The time intervals for the different test periods, the total number of days analyzed and the number of weekdays, weekends and holidays is given in Table 26.

Table 26. Number of days analyzed during pre-retrofit and post-retrofit periods

| | *Number of Days Analyzed Over Course of Testing in Building 988* | | | | | |
|---|---|---|---|---|---|---|
| Test Period | Start | Stop | Total Days | Weekdays | Weekend Days | Holidays |
| Pre-retrofit | 8/26/2010 | 12/19/2010 | 99 | 63 | 31 | 5 |
| Post-retrofit 1 | 5/1/2011 | 12/23/2011 | 190 | 126 | 58 | 6 |
| Post-retrofit 2 | 1/1/2012 | 9/8/2012 | 243 | 169 | 70 | 4 |

The post-retrofit 1 dataset used in analysis consists of 190 days made up of 126 weekdays, 58 weekend days, and 6 holidays that were recorded from May to December 2011. The post-retrofit 2 dataset ran from Jan 2012 until September 8, 2012. This dataset consisted of 169 weekdays, 70 weekend days and 4 holidays.

The following sections present results comparing the pre-retrofit and the post-retrofit 1 study periods. Further energy analyses that include the post-retrofit 2 dataset can be found in Appendix E.

### 6.4.1 Reduce lighting demand

The post-retrofit dataset used in energy analysis consisted of 200 days made up of 136 weekdays, 58 weekend days, and 6 holidays between May and December 2011.

Peak LPD averaged over a 15 minute interval was calculated for each week of data collected. No outliers were identified for either the pre-retrofit of post-retrofit datasets. This resulted in a peak pre-retrofit metered LPD of 0.77W/sq ft, peak adjusted pre-retrofit LPD of 1.11W/sq ft, and peak post-retrofit LPD of 0.86W/sq ft. Note that peak post-retrofit LPD is well below the installed post-retrofit level of 1.31 W/sq ft. This means that lights throughout the study area were not operating at full power simultaneously during the post-retrofit period. The reduction is likely

due to a combination of tuning, daylight harvesting and lights being turned off in unoccupied spaces.

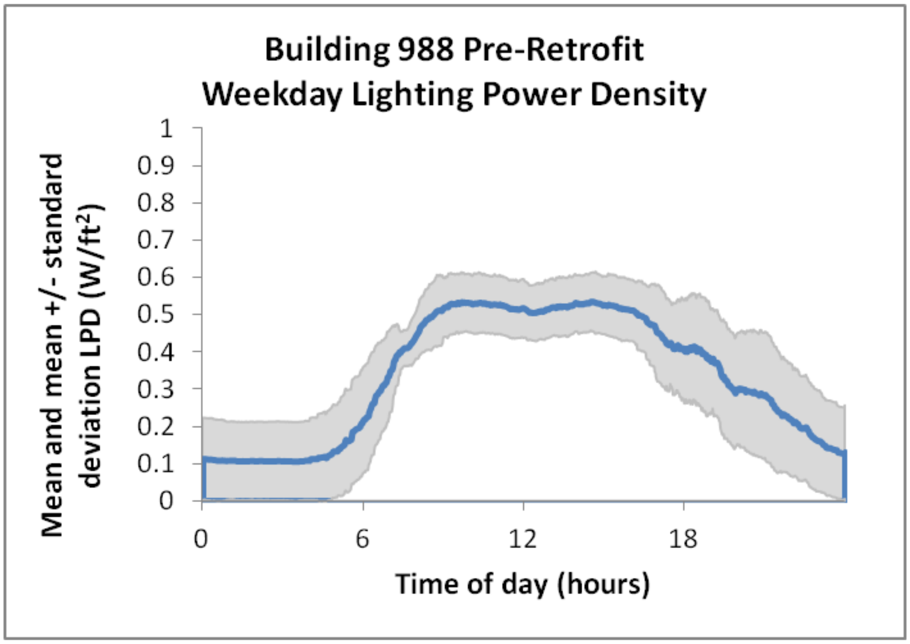



Figure 35: Pre-retrofit LPD in building 988

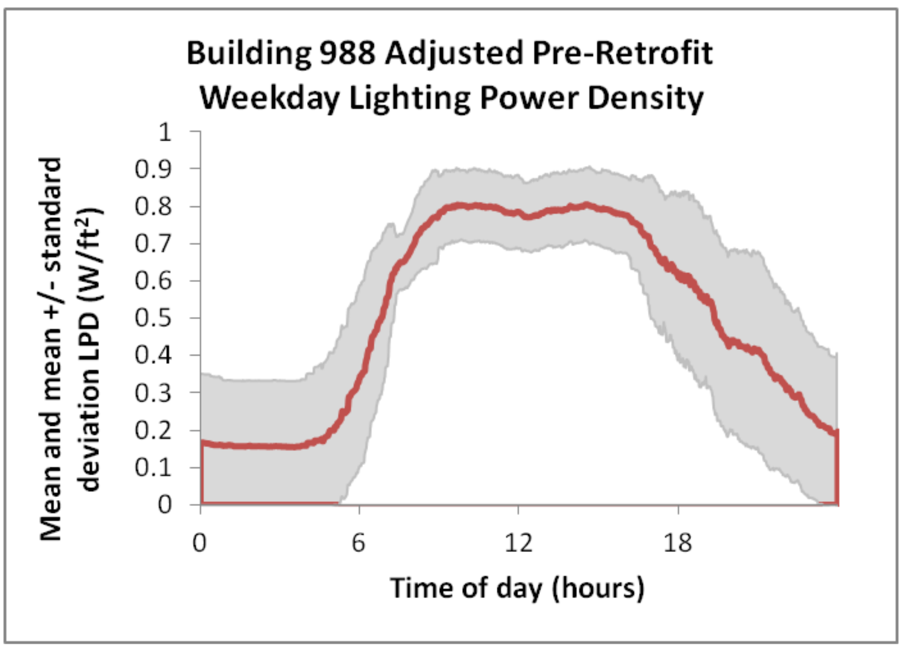



Figure 36: Adjusted pre-retrofit LPD in building 988

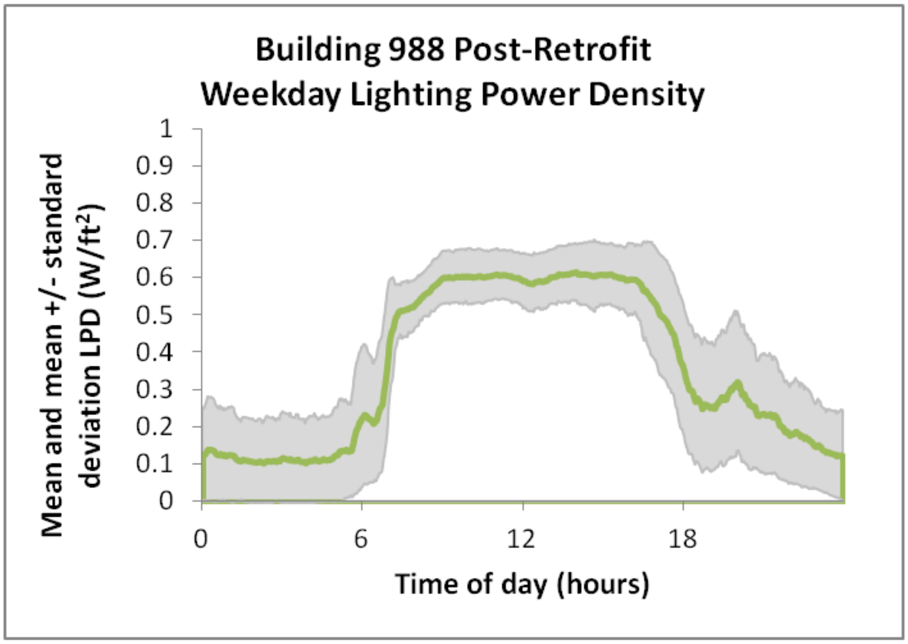



Figure 37: Post-retrofit LPD in building 988

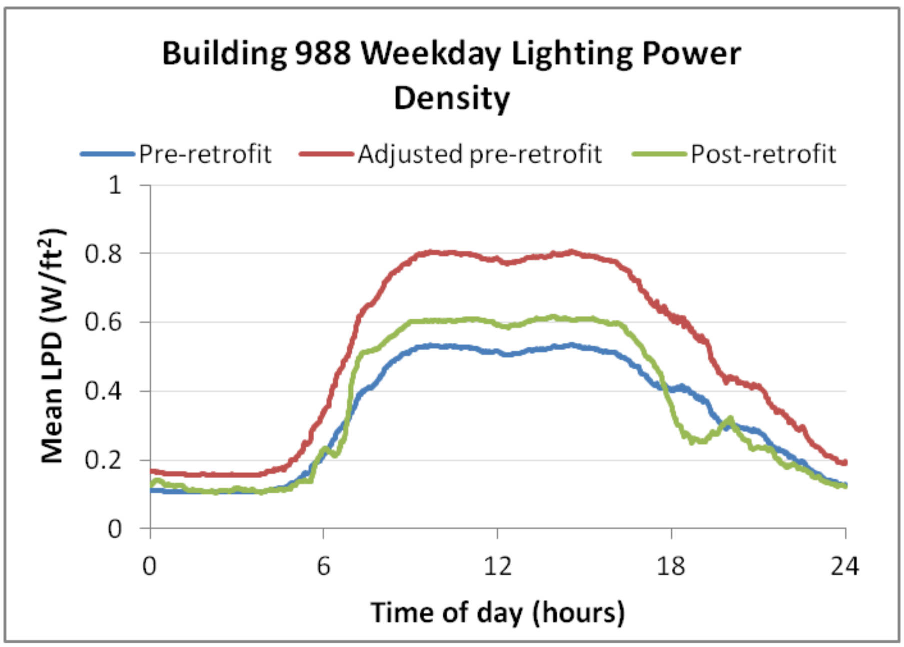



Figure 38: LPDs in building 988

The goal was to achieve at least a 25% reduction in peak LPD compared to the code baseline. The results show a 52% reduction compared to the code baseline, substantially exceeding the target. The retrofit also resulted in a 23% reduction compared to the adjusted pre-retrofit and a 14% reduction compared to the 2007 reference code level of 1.00 W/sq ft. The retrofit increased the peak LPD by 12% compared to the metered pre-retrofit, however, largely due to re-lamping in the large open office area.

Table 27: Building 988 peak LPD results

| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline | Post-retrofit metered | Percent savings compared to… Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
|---|---|---|---|---|---|---|---|
| Peak LPD over a 15 minute period (W/sq ft) | 0.77 | 1.11 | 1.81 | 0.86 | -12% | 23% | 52% |

### 6.4.2 Reduce electrical energy use for lighting

Daily and annual energy results are presented below in Table 28. Annual EUI is calculated from average daily EUIs based on an assumed 251 weekdays, 104 weekend days, and 10 holidays per year. For the pre-retrofit data, which exhibited statistically significant variation associated with day of the week, weekday EUI was calculated as an average of the EUI associated with each day of the week.

Table 28: Building 988 EUI results

| | Pre-retrofit | Adjusted pre-retrofit | Code baseline | Post-retrofit | Percent savings compared to… Pre-retrofit | Adjusted pre-retrofit | Code baseline |
|---|---|---|---|---|---|---|---|
| Weekday energy use intensity (Wh/sq ft/day) | 8.02 | 12.14 | 18.1 | 8.68 | -8.2% | 28.5% | 52.0% |
| Weekend energy use intensity (Wh/sq ft/day) | 3.77 | 5.76 | 0 | 3.58 | 5.0% | 37.8% | N/A |
| Holiday energy use intensity (Wh/sq ft/day) | 5.06 | 7.73 | 0 | 4.64 | 8.3% | 40.0% | N/A |
| Annual energy use intensity (kWh/sq ft/yr) | 2.46 | 3.73 | 4.54 | 2.60 | -5.7% | 30.3% | 42.8% |

Analysis of the post-retrofit dataset shows an average weekday EUI of 8.68 Wh/sq ft/day, weekend EUI of 3.58Wh/sq ft/day, and holiday EUI of 4.64 Wh/sq ft/day. As shown in Table 28, this results in an annual EUI of 2.60 kWh/sq ft/day. The retrofit resulted in 43% annual savings compared to the code baseline and 30% savings compared to the adjusted pre-retrofit. Energy use increased by 6% and 3% compared to the pre-retrofit metered and the 2007 reference code, respectively due to the fact that with relamping, the installed lighting power was increased to address the occupant dissatisfaction that existed before the retrofit. In general, the post-retrofit lighting control system significantly reduced weekday EUI compared to the adjusted pre-retrofit.

Energy use was much higher in this building than in the other buildings during both study periods. This was largely due to very long operating hours in the foyer area and in the surveillance room at the front of the building, both of which had at least some lights on nearly 24 hours/day for much of both study periods. The guard room is occupied 24 hours/day throughout the year which resulted in high energy use on weekends and holidays. These unusual use patterns increased energy use significantly relative to the code baseline, which assumed no use on weekends or holidays.

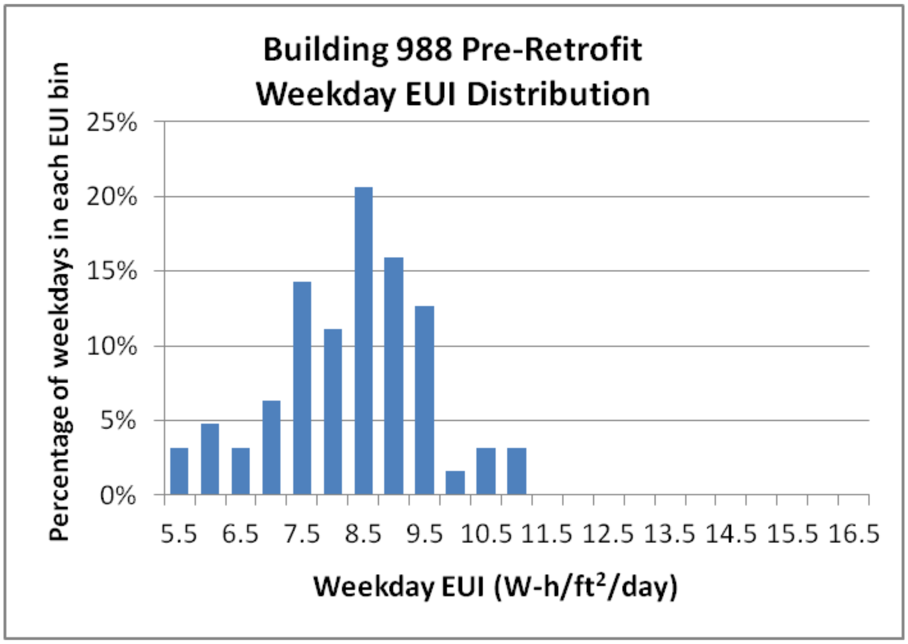



Figure 39: Pre-retrofit weekday EUI in building 988

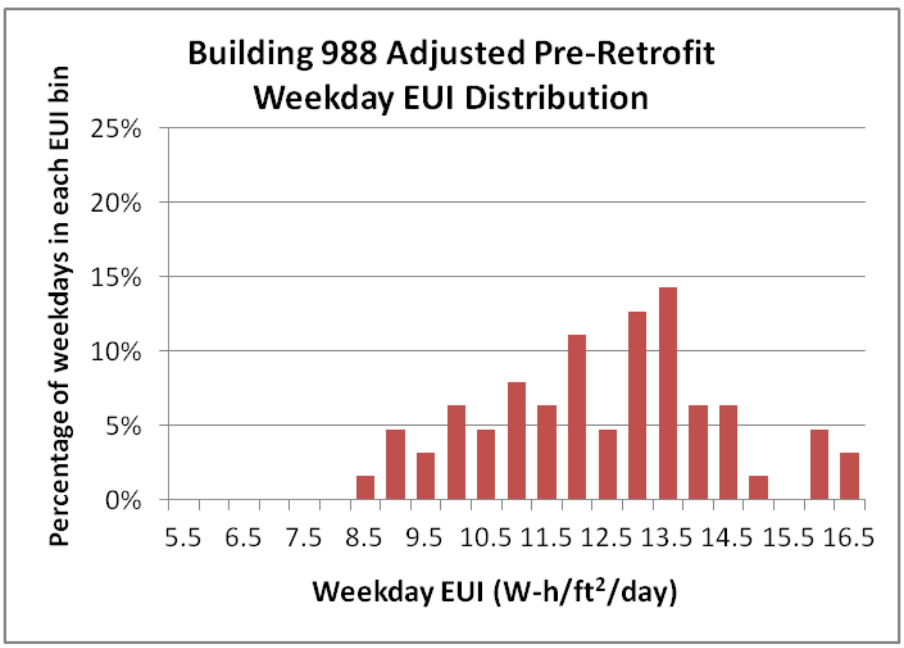



Figure 40: Adjusted pre-retrofit weekday EUI in building 988

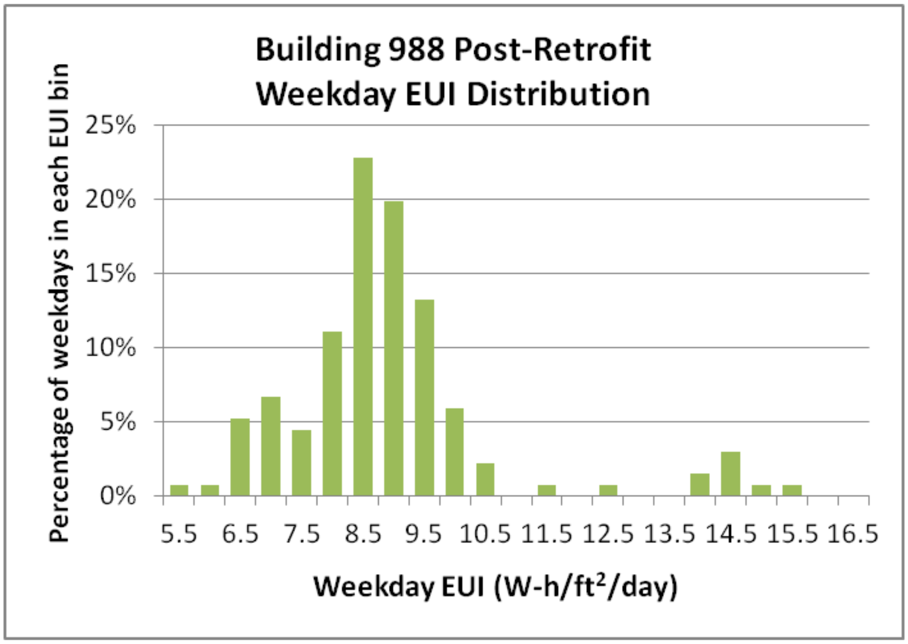



Figure 41: Post-retrofit weekday EUI in building 988

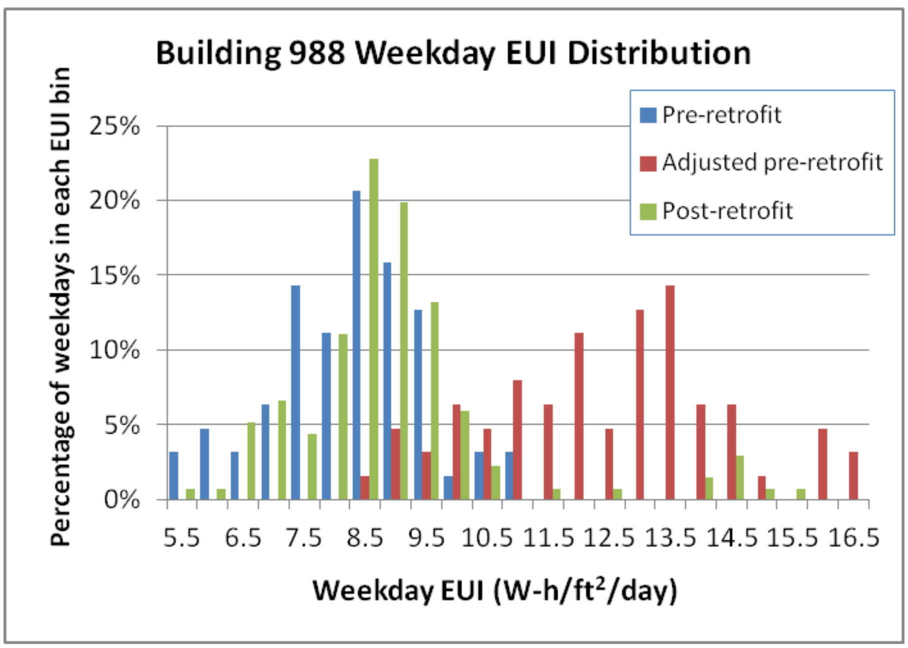



Figure 42: Weekday EUIs in building 988

The goal was to demonstrate at least a 45% reduction in annual EUI compared to the code baseline. The results show a 43% reduction, which comes close to the goal but fails to meet it. It is worth pointing out that 3 ballasts were replaced in study area without the knowledge of project team. Since the new ballasts were not configured to receive control system commands

they did not respond to the control messages. This lead to some lights remaining on 24 hours/day for about 14 days until the issue was discovered by the project team and ballasts were configured to receive control system commands. This issue resulted in weekday energy use approximately 70% higher than energy use when the system was working correctly. This error increased overall weekday energy use by nearly 5%. If the project team was made aware of the issue in timely fashion then energy wasted by inadvertent burning of lights which contributed to about 5% of overall weekday energy use would have been avoided helping the system to demonstrate at least 45% reduction in annual EUI compared to the code baseline.

6.4.2.1 Breakdown of energy consumption by space type

Analyzing the results by space types gives more insights into system performance.

The installation area in building 988 was served by five lighting branch circuits, which were individually metered. Table 29 summarizes the different spaces that were monitored, the control strategies that were tested, and details the lighting equipment and lighting power densities for the situation prior to the retrofit (pre-retrofit) and the situation after the controls were installed and commissioned (post-retrofit).

The adjusted pre-retrofit and post-retrofit metered average weekday lighting EUI is plotted in Figure 43. The pre and post-retrofit measurements were used to project the annual lighting energy use (Figure 44) and the annual lighting energy savings (Figure 45) for each of the five measured zones. Savings are calculated using the adjusted pre-retrofit.

Table 29: Summary of pre-retrofit and post-retrofit lighting systems in building 988

| Space Description | Area (sf) | Pre-retrofit | | | Post-retrofit | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | # of fixtures | # of lamps | Original LPD (W/sf) | # of fixtures | # of lamps | Installed LPD (W/sf) | # of multi-sensors | Lighting Control Strategies Tested |
| Five mixed use rooms | 1,327 | 17 | 39 | 0.88 | 21 | 63 | 1.6 | 6 | Occupant Sensing & Task Tuning |
| Conference room | 1,026 | 11 | 33 | 0.96 | 11 | 33 | 1.08 | 3 | Occupant Sensing & Task Tuning |
| Five perimeter offices | 1,069 | 19 | 57 | 1.6 | 19 | 57 | 1.8 | 5 | Occupant Sensing, Task Tuning & Daylighting |
| Five mixed use areas | 1,047 | 14 | 36 | 1.03 | 14 | 36 | 1.17 | 5 | Occupant Sensing |
| Open plan cubicles | 2,706 | 30 | 60 | 0.65 | 30 | 90 | 1.12 | 12 | Occupant Sensing |
| **Overall** | **7,177** | **91** | **225** | **0.94** | **95** | **279** | **1.31** | **31** | |

Significant energy savings were measured in the two areas with mixed use as well as in the five perimeter offices. Projected annual energy use was decreased by nearly 2 kWh/sf/year in these mixed use areas which translates into energy savings of 40 – 58%. Also, 40% energy savings was obtained in the five perimeter offices resulting in an annual decrease of 0.6 kWh/sf/yr.

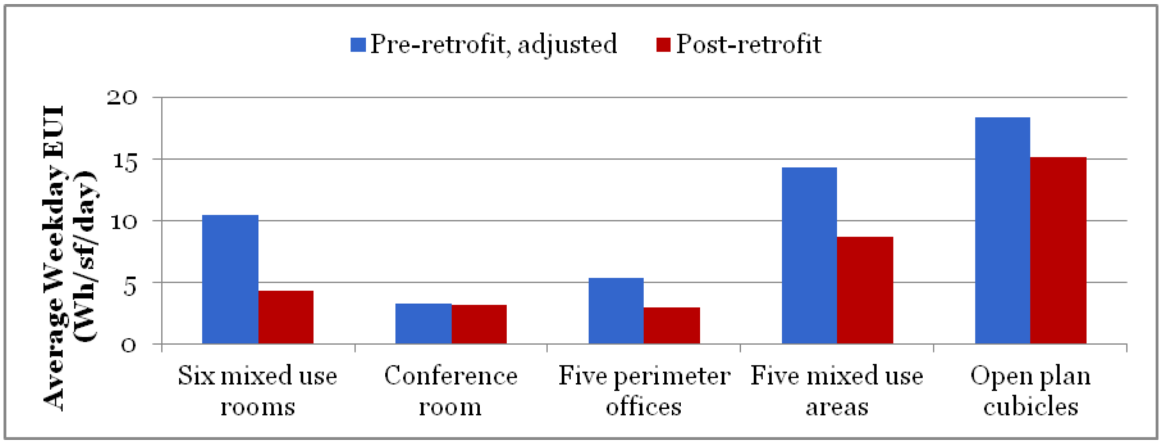



Figure 43: Average weekday EUI for five metered zones.

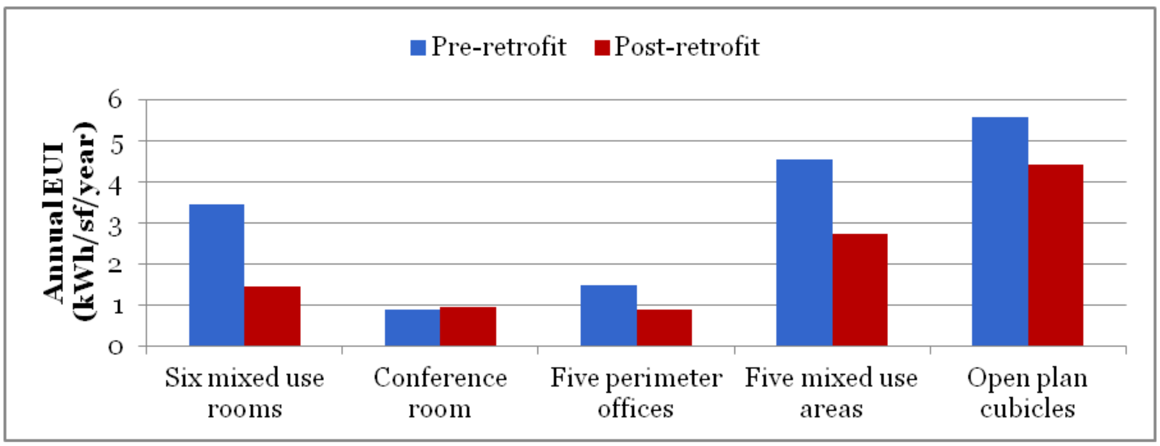



Figure 44: Projected annual lighting EUI for each of the five metered zones

Energy use is much higher in the mixed use rooms and areas largely due to very long operating hours in the foyer area at the front of the building which had at least some lights on nearly 24 hours/day. The guard room is occupied 24 hours/day throughout the year which resulted in high energy use on weekends and holidays. In spite of the unusually high usage and negligible daylight, the control system saved a significant amount of energy (40%-56%) mainly due to occupancy sensing in utility areas (e.g. restrooms, janitor's room, vending room, copy room and storage room) which afforded many opportunities for savings. In addition, there was some energy savings due to the fact that occupants in these spaces had access to scene switches that allowed them to choose a light level other than maximum.

Results indicate that EUI in the conference room is very low relative to other spaces which is due to lower usage pattern. The post-retrofit EUI is higher than the pre-retrofit EUI primarily due to increased usage. Anecdotal evidence has suggested that users liked the scene setting features of control system which lead to increased usage of retrofitted conference room over other non-retrofitted conference rooms in the building.

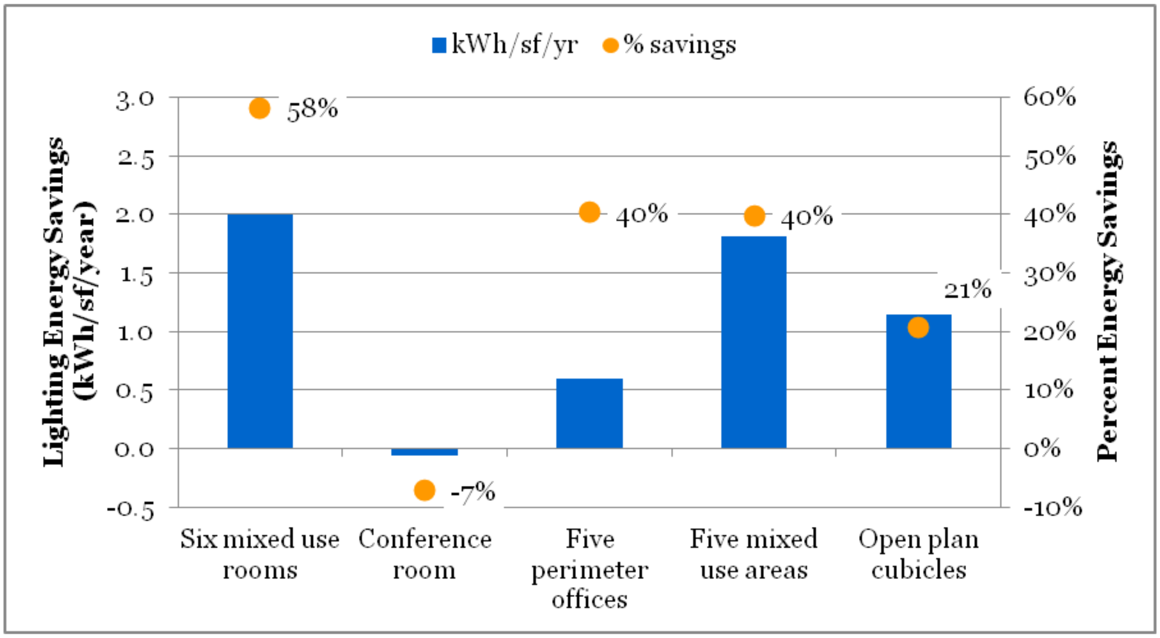



Figure 45: Projected annual lighting energy savings (left scale) and percent energy savings (right scale)

Energy use in private offices is also relatively low compared to open plan office areas. Even with a low baseline EUI, the control system was able to save 40% energy due to a combination of occupancy sensing, daylight harvesting and task tuning. Peak LPD analysis showed that peak LPD in private office area was reduced by 43.6% which indicates that a significant portion of the savings accrued due to task tuning and daylight harvesting.

Energy use in the large open office area that accounts for only 38% of the study area's floor space is quite high. The circuit controlling lights in this area has the highest adjusted pre-retrofit and post-retrofit weekday EUI. This high energy use and large floor area mean that open office energy use has a large impact on total energy use: The open office circuit contributes 56%, and 64% of total annual energy use for the adjusted pre-retrofit and post-retrofit system, respectively even though it served only 38% of the study area's floor space. Since the open plan area does not receive any daylight and occupants in this space wanted higher light levels, the savings are almost entirely due to occupancy sensing.

The energy savings potential of typical occupancy sensing based controls in open office areas can be limited. Many people often move through open offices throughout the day, which means lights can stay on continuously during operating hours despite added occupancy control. The number of open office occupancy sensing control zones can have a large impact on results, with more zones corresponding to higher savings. Savings depend largely on occupancy patterns and sensor range and placement. This open office area is broken into five zones. The control system turns off the lights in one or more unoccupied zones which saves energy throughout the day but more so towards the end of workday.

Finally, since occupancy sensors turn lights on for a preconfigured timeout period when triggered, occupancy sensors can increase energy use by turning lights on when someone enters a space for a very short period of time. During the pre-retrofit period, lights in the open office typically stayed on during the day and off after-hours, with all the lights in the area seldom left on overnight. In contrast, while lights do not stay on all night during the post-retrofit period, there are a significant number of after-hours events when all or some of the lights turn on for a short period of time. These events are likely due to someone entering the space for a short period of time (e.g. night guards, cleaning crew), triggering some or all of the occupancy sensors, and then leaving. One way to reduce the energy loss associated with this type of event is to implement shorter timeouts after-hours.

### 6.4.3 Reduce carbon footprint of the lighting system

The carbon footprint of the code baseline, pre-retrofit metered, adjusted pre-retrofit, and post-retrofit system are presented in Table 30. Percentage savings are also indicated in the table. All emissions are based on an emission factor of 1.045 lbs $CO_2$/kWh.

Table 30: Building 988 carbon footprint

| | | | | | Percent savings compared to… | | |
|---|---|---|---|---|---|---|---|
| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline | Post-retrofit metered | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
| Annual $CO_2$ emissions (lbs/sq ft/yr) | 2.57 | 3.90 | 4.75 | 2.71 | -6% | 30% | 43% |

The goal was to demonstrate at least a 45% reduction in carbon footprint compared to a building with code baseline lighting energy use in the same region. Results show a 43% reduction compared to the code baseline, which comes close to the goal but fails to meet it. As mentioned earlier, if the project team was made aware of the ballast replacements in timely fashion then energy wasted by inadvertent burning of lights which contributed to about 5% of overall weekday energy use would have been avoided helping the system to demonstrate at least 45% reduction carbon footprint compared to a building with code baseline lighting energy use in the same region.

### 6.4.4 Cost-effectiveness

See section 7 Cost Assessment for a detailed discussion on cost-effectives.

### 6.4.5 System reliability

The Dynalite lighting control systems utilize a distributed processing architecture in which each component incorporates a microcontroller and non-volatile memory. These components are configured to behave autonomously by storing parameters in their non-volatile memory using

commissioning software. This distributed processing architecture is robust against a single point of failure. Should a single device fail, all other devices will continue to operate as normal. Moreover, the wired architecture is inherently reliable in addressing signal propagation and interference issues. No system-wide failures were noticed during the demonstration period. Note that there were a few incidences of power outages during the demonstration period however, Dynalite system automatically recovered when power was restored. Thus, Dynalite exceeded the success criteria for the reliability metric.

#### 6.4.6 System maintainability

The Dynalite system in building 988 has worked satisfactorily throughout the demonstration period. There was one system performance issue noticed by the project team. During 14 days in late October 2011, energy use increased significantly on two of the five circuits in the study area. Project team decided to investigate the cause of increase in energy consumption. The Dynalite system has features that allow status of components to be queried remotely thereby detecting any issues if any component fails to respond to query messages. Using this diagnostic feature, a report was generated which found that 3 ballasts had not responded to query messages. Follow up site visits revealed that these ballasts were replaced without the knowledge of project team.

This highlights the need for robust automated diagnostics in lighting controls installations. An automated anomaly detection system can alert maintenance personnel and expedite the resolution thereby reducing the downtime and preventing energy wastage.

Table 31: Maintenance record of Dynalite system in building 988

| Month | Scheduled Maintenance | | Unscheduled Maintenance | |
|---|---|---|---|---|
| | Actions | Downtime Hrs | Actions | Downtime Hrs |
| May | 0 | 0 | 0 | 0 |
| June | 0 | 0 | 0 | 0 |
| July | 0 | 0 | 0 | 0 |
| August | 0 | 0 | 0 | 0 |
| September | 0 | 0 | 0 | 0 |
| October | 0 | 0 | 1 | 0 |
| November | 0 | 0 | 0 | 0 |
| December | 0 | 0 | 0 | 0 |

The objective was to show no more than 4 scheduled maintenance actions per month and no more than 8 hours of scheduled maintenance downtime per month. Additionally, system should require no more than 2 unscheduled maintenance actions per month and no more than 4 hours of unscheduled maintenance downtime per month. Results in Table 31 indicate that Dynalite met these success criteria.

6.4.7 Workplane illuminance

The post-retrofit survey took place on June 29, 2011, between 11:30 pm and 2am. Of the 32 pre-retrofit measurement locations, locations outside offices and conference rooms and those that did not have a matching post-retrofit illuminance measurement were eliminated. This left 10 measurements in private offices and 6 in the open office. The post-retrofit measurements ranged from 400-742 lux in the open office area and from 381-629 lux in private offices and the conference room. Results are presented below in Figure 46.

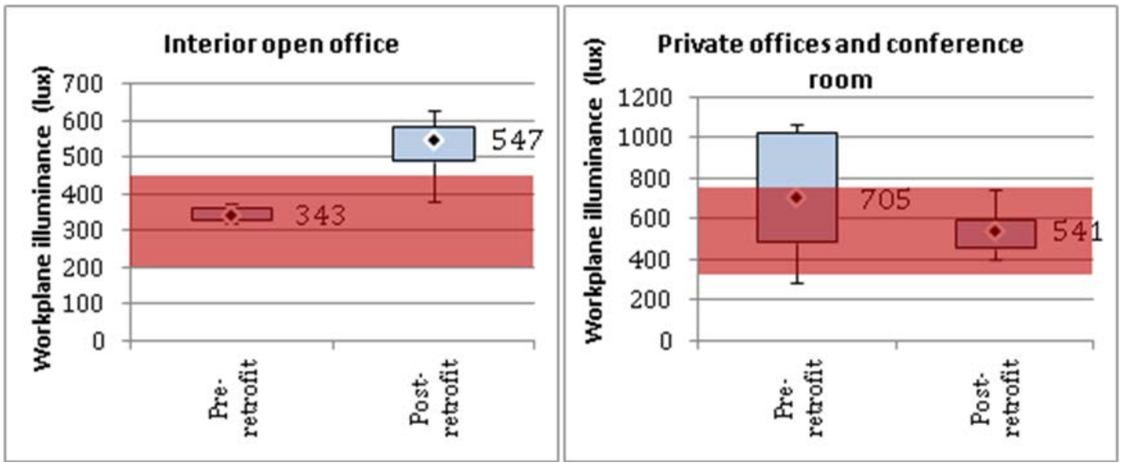



Figure 46: Pre-retrofit and post-retrofit tuned workplane illuminance levels in building 988

Baseline and post-retrofit light measurements were analyzed in terms of the average deviation from the acceptable range over the set of measurements. In the open office, all pre-retrofit measurements fell between 300 and 400 lux, a tight range well inside the target range. Post-retrofit measurements, on the other hand, varied more widely, with 5 out of the 6 measurements above the target range. In private offices and the conference room, pre-retrofit measurements varied widely, with many very high values. Five of the 10 pre-retrofit measurements fell above the target range, and 2 fell below. All post-retrofit measurements in private offices and the conference room fell within the target range.

Table 32: Building 988 illuminance results

| Performance objective | Pre-retrofit metered | Post-retrofit metered | Percent improvement from pre-retrofit metered |
|---|---|---|---|
| Average deviation from specified illuminance range in open office (lux) | 0 | 89 | -Inf |
| Average deviation from specified illuminance range in private offices and conference rooms (lux) | 123 | 0 | 100% |

The objective was to show at least a 10% reduction in average deviation from the DPW requirement over the average deviations prior to upgrade. This criterion was not met in the open

office and was met in the private offices and conference room. Over both sets of measurements, the average pre-retrofit deviation is 77 lux and average post-retrofit deviation is 24 lux, a 69% reduction, exceeding the success criterion.

The retrofit significantly increased open office light levels and significantly decreased private office light levels. The fact that post-retrofit open office light levels are mostly well above the specified range highlights complications typical of setting illuminance targets. Though pre-retrofit levels in the open office were all inside the target range, DPW requested increased light levels to address occupant complaints about inadequate illuminance. Based on this request, fixtures were re-lamped with three lamps per fixture during the retrofit. The post-retrofit system responded to DPW's request and addressed the occupants' needs, but in doing so increased deviation from the target illuminance range. One way of addressing this may be to assume based on DPW's request that the target range in this particular open office should be the same as the private office target of 333-750 lux. In this case neither the pre-retrofit nor the post-retrofit systems deviated significantly from the range, though the pre-retrofit system has three out of six readings slightly below the range whereas the post-retrofit system has all the measurements within this range.

In the private offices and conference room, the retrofit corrected an extremely wide range of pre-retrofit light levels, and brought all measurements within the target range. The use of dimmable ballasts allowed commissioning agents to tune the lights to target levels and provide more uniform light distributions without changing the fixture layout.

#### 6.4.8 Ease of commissioning and installation

The installers found the Dynalite system installation fairly straightforward. One installer said all tasks were very straightforward except for sensor placement and installation, which he rated as somewhat straightforward. The other installer said all tasks were somewhat straightforward except for wall switch replacement and sensor placement and installation, which he rated as neutral. One installer mentioned that initially it was not clear where they should place the sensors and had to move a few sensors, but that this was not a big issue.

In response to a variety of qualitative questions, installer responses included:

- Both installers were neutral or disagreed with the statements "The project presented installation challenges that I was not familiar with" and "the installation took longer and required more effort than typical installations of a similar size".
- Both were neutral as to whether they could have performed the installation with minimal support beyond written materials.
- Both strongly agreed that they could perform future installations of the same systems with minimal support.
- Both were neutral or agreed that written instructions were clear and comprehensive.
- Both were neutral in response to a question asking if they had concerns that problems could have come up during the installation process.

Both installers mentioned that they had some questions along the way, but that with minimal support the installation did not present any significant challenges. They generally seemed happy with the system and the installation process.

#### 6.4.9 User satisfaction

Only 4 out of 8 occupants responded to the pre-retrofit survey, and only 1 out of 9 responded to the post-retrofit survey. DPW did not send a reminder email to the post-retrofit occupants out of concern about disturbing them. The low number of people surveyed and single post-retrofit respondent limited the extent to which results can be considered representative. It is not possible to say if occupant satisfaction improved overall; however, some insight still emerged from the responses.

The surveys found that:

- Half of the pre-retrofit respondents found their lighting comfortable and half did not; the single post-retrofit respondent found their lighting comfortable.
- The two pre-retrofit occupants who answered the question were both not satisfied with their ability to control their lights, while the single post-retrofit occupant was satisfied.
- The two pre-retrofit respondents who answered a question about what they would like changed about their workspace lighting listed the ability to control light levels among their selected options, while the post-retrofit occupant did not.

In general, the single post-retrofit respondent appeared content with their workspace lighting and controls, while the pre-retrofit respondents appeared less content. However, as noted above, it is not clear if these results are representative due to the small number of people surveyed and the small number of responses.

#### 6.4.10 System Integration

To study the effects of the Dynalite system on HVAC energy consumption the DoE small office reference model post-1980 construction (V1.3_5.0 migrated to EnergyPlus V7.0) for climate zone 3B was used. This model represents a rectangular single-floor (511m$^2$) office building with core and perimeter zoning and attic space (top view shown in Figure 33).

The analyze the system integration objective, the small office reference model was modified to represent the code baseline lighting energy use. Then, the lighting power in the model was modified such that the annual lighting energy savings over the code baseline was the same as the post-retrofit savings over the code baseline. In this case, the analysis is based on the annual EUI savings due to Dynalite over the code baseline (43%).

Simulations were run in EnergyPlus. Results are shown in Figure 47 and summarized in Table 33.

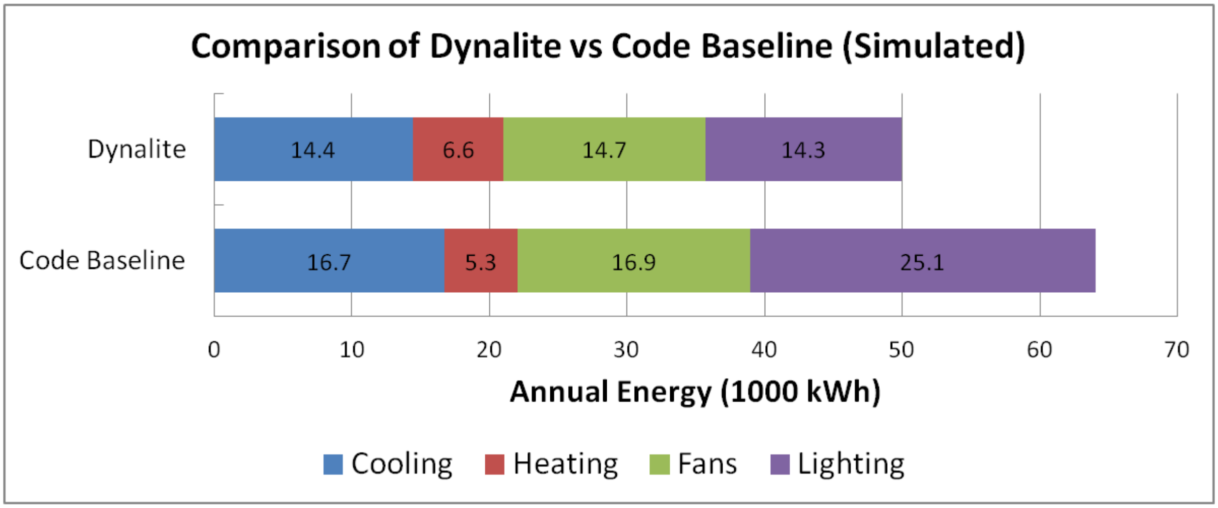



Figure 47: Comparison of Dynalite performance versus code baseline (simulated)

Table 33: Annual energy savings due to Dynalite over code baseline by subcategory (simulated)

| | Lighting | Cooling | Heating | Fans | HVAC |
|---|---|---|---|---|---|
| Dynalite | 43.0% | 13.8% | -24.2% | 13.2% | 8.4% |

The results with respect to the system integration performance objective for Dynalite are shown in Table 34. The success criterion was to show greater than 5% savings in HVAC energy consumption compared with code baseline HVAC energy consumption. Clearly, the simulated Dynalite system exceeded the performance target.

Table 34: Dynalite system integration results

| Performance objective | Code baseline HVAC energy consumption (1000 kWh/year) | Dynalite HVAC energy consumption (1000 kWh/year) | % HVAC savings |
|---|---|---|---|
| System Integration | 38.9 | 35.7 | 8.4% |

## 6.5 PERFORMANCE RESULTS SUMMARY

Table 35 summarizes the performance of 3 technologies against the objectives stated in Table 3. As can be seen from the table, most of the objectives were met during the demonstration with exception of two which are discussed below.

Table 35: Performance results

| Performance Objective | Success Criteria | Results: Hybrid ILDC | | | OccuSwitch | | | Dynalite | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reduce electrical energy consumption for lighting | >45% reduction in EUI compared with code baseline lighting energy | 79% | | | 62% | | | 43% | | |
| | | Y | | | Y | | | Y in 80% space | | |
| Reduce lighting demand by better lighting design | >25% reduction in Peak LPD compared with code baseline LPD | 60% | | | 47% | | | 52% | | |
| | | Y | | | Y | | | Y | | |
| Reduce Carbon footprint of the lighting system | >45% reduction in carbon footprint compared to a building with code baseline lighting energy in the same region | 79% | | | 62% | | | 43% | | |
| | | Y | | | Y | | | Y in 80% space | | |
| Cost-Effectiveness | Building size | Sm | Md | Lg | Sm | Md | Lg | Sm | Md | Lg |
| | >2 SIR over a 20 year period | 1.6 | 2.8 | 3.4 | 1.8 | 2.8 | 4.4 | 1.2 | 1.6 | 2.4 |
| | | N | Y | Y | N | Y | Y | N | N | Y |
| | <7 years Payback | 6.25 | 3.89 | 3.09 | 5.37 | 3.56 | 2.28 | 8.67 | 6.47 | 4.29 |
| | | Y | Y | Y | Y | Y | Y | N | Y | Y |
| System Reliability | No more than 3 system-wide failures per system in a 3 month time window | 0 | | | 0 | | | 0 | | |
| | | Y | | | Y | | | Y | | |
| System Maintainability | No more than 4 scheduled maintenance actions per system per month and no more than 8 hours of scheduled maintenance downtime per system per month. | <=1/mo | | | <=2/mo | | | <=1/mo | | |
| | | 0 hr | | | 0 hr | | | 0 hr | | |
| | | Y | | | Y | | | Y | | |
| | No more than 2 unscheduled maintenance actions per system per month and no more than 4 hours of unscheduled maintenance downtime per system per month | <=1/mo | | | <=1/mo | | | <=1/mo | | |
| | | 0 hr | | | 0 hr | | | 0 hr | | |
| | | Y | | | Y | | | Y | | |
| Work plane Illuminance | >10% reduction in average deviation from the DPW requirement over the average deviations prior to upgrade. | 98% | | | 73% | | | 69% | | |
| | | Y | | | Y | | | Y | | |
| Ease of installation and commissioning | Installer survey indicates that installers can install and commission systems with minimal training | Y | | | Y | | | Y | | |

| | | | | |
|---|---|---|---|---|
| User satisfaction | User satisfaction survey indicates improved satisfaction with performance | Statistically insignificant responses | | |
| System Integration | >5% reduction in HVAC energy compared with code baseline HVAC energy | 7.7% – 15.6% | 11.6% | 8.4% |
| | | Y | Y | Y |

As shown in Table 35, the three systems performed differently with respect to energy savings as expressed in EUI/carbon footprint reduction, peak lighting power density and cost effectiveness. This is partly due to the differences in the characteristics of the buildings they were deployed in and partly due the energy savings features of the systems. For instance the size of the buildings is an important parameter that determines the system cost per unit area as fixed hardware cost, such as servers and controllers are amortized over the entire area. To provide a more generalized picture that can be applied across the entire DoD facilities, three different building size scenarios have been considered – small, medium and large defined specifically in section 7.5. With this classification, it is seen that payback <7 years is met in most cases with the exception of the small area category for the Dynalite system. Savings to investment ratio objective (>2) is met in the large buildings for all three systems and medium buildings for Hybrid ILDC and OccuSwitch systems. In small buildings the SIR objective is not met.

While on the average for the three systems taken together the performance well exceeded the key targets (energy cost and carbon footprint), the Hybrid ILDC and OccuSwitch systems met or exceeded these key performance objectives. Dynalite achieved 43% reduction in EUI compared with code baseline lighting energy against the target of at least 45% reduction in EUI, marginally falling short of the target. However, upon closer examination of the data, it is subject to interpretation for the following reasons:

1. The selected areas in building 988 consisted of several circuits representing a variety of space types namely, conference rooms, offices, lobby/offices and theater and storage. Some of these areas, such as conference rooms and lobby areas varied in energy usage depending on the occupancy pattern.
2. In the case of the conference room , for example, the energy consumption was nearly the same as pre-retrofit or actually went up slightly, even though they has adjustable light levels, scene setting modes and occupancy sensors, all of which are expected to lower the energy consumption. The reason for the unexpected rise in energy consumption is most likely that the advanced features of the lighting in the room (especially scene setting modes – presentation, meeting, etc.) attracted more users and thus increased usage than that during the pre-retrofit period.
3. Furthermore, in one of the areas, 3 ballasts were inadvertently replaced without our knowledge and lights were left on at full power for nearly three weeks. This error increased overall weekday energy use by nearly 5%.

In spite of all this, in 80% of the circuits serving the areas the energy savings success criteria were met. So overall, it is expected that had we implemented the Dynalite lighting controls in the

entire building and the error in ballast replacement were not made, the energy savings average would have been higher exceeding the target of 45% savings over code baseline.

With respect to system reliability, system maintainability, work plane illuminance and ease of installation and commissioning all three systems met the objectives with significant margin. This is a testimony to the robustness of the systems in general and are independent of building characteristics.

Unfortunately, the results of user satisfaction survey were statistically insignificant. DPW was only able to identify four occupants for the user satisfaction survey in building 279 during both the pre-retrofit and post-retrofit study periods. Out of 4 occupants who were sent survey questionnaires, one person responded to the survey during the pre-retrofit period, and two responded during the post-retrofit period. In building 988, only 4 out of 8 occupants responded to the pre-retrofit survey, and only 1 out of 9 responded to the post-retrofit survey. DPW did not send a reminder email to the post-retrofit occupants out of concern about disturbing them. The extremely low number of people surveyed limited the extent to which results can be considered representative. Nonetheless some insights still emerged from the responses which are captured above.

Systems integration performance, or the effect of the lighting control systems on the HVAC load, as computed from Energy Plus model based simulations are consistent with expectations and met the project objectives. It should be pointed out that, the actual energy savings performance of the HVAC systems will be dependent on the type and effectiveness of the HVAC systems deployed in the buildings.

Overall this demonstration project has shown that advanced lighting control systems deployed in existing DoD buildings can provide significant energy cost and carbon footprint reduction ranging from 43% to 79% depending on the building geometry, legacy system deployed and usage pattern. The three systems varied in terms of features and performance, each one being optimal for a certain class of building types. For large buildings (over 100,000 sq.ft.) networked systems such as the Dynalite or Hybrid ILDC are expected to provide the best results whereas for medium to small sized buildings standalone room based systems such as the OccuSwitch Wireless system would be more appropriate.

# 7 COST ASSESSMENT

In this section the life-cycle cost, savings-to-investment ratio and simple payback period of three lighting control technologies deployed at Ft. Irwin are evaluated to assess the cost-effectiveness of these systems.

## 7.1 COST MODEL

The cost model developed for analysis encompasses design, material acquisition, installation, commissioning, supervision, inspection and cost of maintaining lighting control systems. The relevant cost elements and data tracked during the demonstrations are mentioned in Table 36.

Table 36: Cost model for the lighting control system

| **Cost Element** | Description | Data Tracked During the Demonstration |
|---|---|---|
| **Design** | Developing design documents and layout plans for the installation of lighting control system | 10% of total investment in technology as recommended by BLCC |
| **Hardware material costs** | Capital costs of hardware used in the demonstration | Control Equipment (e.g. Sensors, ballast controllers, dimmers, switches, control panels) quantities and costs |
| | | Lamps and Fixtures quantities and costs |
| | | Blinds and accessories quantities and costs |
| | | Computer and software itemized costs |
| | | Networking gear (e.g. Ethernet switches, zone controllers) quantities and costs |
| | | Cables, materials and supplies |
| **Installation costs** | Labor required to install and wire the system | Installation labor rate ($/hr) |
| | | Installation time |
| | | Installation supplies and material cost |
| **Commissioning cost** | Labor required to commission and test the system | Hours spent on commissioning and testing |
| | | Labor rate for commissioning and testing in ($/hr) |
| | | Commissioning tools and supplies cost |

| | | |
|---|---|---|
| **Supervision, inspection and overhead** | Cost of supervising and inspecting the lighting systems and associated overheads | 6% of total investment in technology as recommended by BLCC |
| **Base electric energy costs** | Cost of energy used to power lighting systems | Unit electric energy prices ($/kWhr) |
| | | Energy price projections published annually on April 1 by DoE in *Discount Factors for Life-Cycle Cost Analysis, Annual Supplement to NIST Handbook 135*. |
| | | Baseline and post retrofit lighting energy usage data (kWhr/yr) |
| **Electric energy costs due to demand charges** | Peak demand charges for the electrical energy used to power lighting systems | Demand charges ($/KW) |
| | | Baseline and post-retrofit peak lighting demand (W) |
| **HVAC energy cost savings** | HVAC energy cost savings due to lighting upgrades | Simulation results on HVAC energy savings due to lighting upgrades (kWhr) |
| **Utility Rebates/Incentives** | Utility rebates for upgrading the lighting system | Utility rebate for upgrading the lamp ($/lamp) |
| | | Utility rebate for upgrading the fixture ($/fixture) |
| | | Utility rebate for upgrading the sensor ($/sensor) |
| **Maintenance costs** | Cost of replacing lamps and batteries; cost of upgrading software | Lamp life (hrs) |
| | | Lamp quantity |
| | | Cost of a new lamp ($/lamp) |
| | | Lamp replacement labor rate ($/lamp) |
| | | Lamp hazardous waste handling fee ($/lamp) |
| | | Average hours of operation per year (hrs) |
| | | Average number of lamps replaced per year |
| | | Amortized cost of initial group replacement |
| | | Battery lifetime (Yrs) |
| | | Battery quantity |
| | | Cost of a new battery |
| | | Battery replacement labor cost |
| | | Battery replacement cycles |
| | | Software upgrade costs ($/yr) |
| **System Lifetime** | Service life of lighting control system | 20 Years |

<u>Design cost:</u> The system planning began with site surveys and user requirements analysis. Based on this information, detailed system configuration including system type, area of coverage, location, type and number of control equipment, sensors, and communications links to be

deployed at the site were determined. Design documents and layout plans were developed for the installation of lighting control system. RFQs for selecting electrical subcontractor were prepared. A detailed project plan including material acquisition, installation and commissioning schedules were prepared. As per the BLCC guidelines, the design costs are estimated to be 10% of total investment in the technology.

Hardware material cost: The requisite systems and components are procured in the specified numbers, including spares, and delivered to the site in time for installation. Hardware material costs include capital investment costs for lamps, ballasts, fixtures, blinds, sensors, control equipment, networking gear, computers and supplies needed for lighting control systems. The procurement costs of all these equipment were recorded.

Installation costs: Systems were installed on site as per the layout plans. Main installation tasks include installing lamps, sensors, switches, control panels, load controllers, blinds and communication cables. Furthermore, the fixed output ballasts were replaced by dimming ballasts and rewired accordingly. The man hours spent for installation and the hourly rate of installation contractor was documented for analysis. The cost of material and supplies used for installation were added to derive total installation costs.

Commissioning cost: The system was commissioned by trained technicians and was thoroughly tested. Commissioning steps include identifying, addressing and establishing communication between sensors, ballasts, switches and other devices. Furthermore, scenes and presets are programmed. Sensors and control strategies were field tested and calibrated to derive the optimal placement and settings for the best system performance. Occupancy sensor sensitivity and time delay, photo-sensor set points, dead-bands, dimming rates and dimming profiles are field calibrated. Functional performance tests were conducted to verify and validate the performance of the system against the plan. Corrective measures were applied to remedy any issues found during testing. The time spent on commissioning and labor rate of technicians who commissioned the system were recorded. Overheads, if any, of using specialized commissioning tools and supplies were added to the cost.

Supervision, Inspection and OverHead (SIOH) costs: The cost of supervising the installation and commissioning process is included in supervision costs. Supervision was focused to ensure quality of work, compliance to safety procedures and cleanliness of work environment. After the lighting system is installed and commissioned it was inspected for compliance. Any miscellaneous costs are included in the overhead costs. As per BLCC guidelines, 6% of total investment in the technology is allocated for supervision, inspection and overhead costs.

Electric energy costs for lighting: Electric energy rate schedule sourced from Southern California Edison (SCE) which supplies power to Ft. Irwin is used in life cycle cost estimations. The SCE's General Service Rate Schedule (GS-2) which is offered to medium-sized commercial and industrial customers with demands above 20 kilowatts (kW) and below 200 kW was found suitable for this analysis. Specifically, we used non TOU rates that went into effect on March 1, 2011 (Cal. PUC Sheet No. 48082-E). The electric energy costs for baseline and post-retrofit systems were derived using baseline and post-retrofit energy consumption profiles and energy rates supplied by utility. The monetary savings due to peak demand reduction were calculated

using the peak demand reduction measured over the baseline and the demand charges as per the rate schedule GS-2.

HVAC Energy Cost Savings: The HVAC energy cost savings due to lighting upgrades were derived using simulation results. The annual electric energy costs for baseline and post-retrofit systems were derived using baseline and post-retrofit energy consumption simulation results and energy rates specified in the SCE's General Service Rate Schedule (GS-2). The monetary savings due to peak electric demand reduction were calculated using the peak demand reduction over the baseline peak demand and the demand charges indicated in the rate schedule GS-2. In buildings where heating systems are natural gas based, the natural gas consumption costs for baseline and post-retrofit systems were added.

Utility Rebates/Incentives: Utilities incentivize lighting system upgrades by offering rebates. Cash rebates are offered for each new lamp, fixture and sensor. The total cash rebate was computed based on number of new lamps, fixtures and sensors installed.

Maintenance costs: Maintenance costs comprise of the cost of replacing the burned out lamps and depleted batteries. The key information needed for maintenance cost calculations is highlighted in Table 36. This information was collected and documented during the course of demonstration.

## 7.2 DERIVING THE COST OF COMMERCIAL VERSIONS

One of the main objectives of this demonstration project is to gauge the expected cost-benefits to the DoD due to wide scale deployment of these technologies. Since one of the systems installed (i.e. Hybrid ILDC) is a research prototype which is custom designed and developed for the demonstration, it is reasonable to expect that the capital, installation, commissioning and maintenance costs of these custom designed prototype system is significantly higher than its commercial version.

At Ft. Irwin the Hybrid ILDC system was deployed on a private dedicated network to expediate its deployment. In order to utilize existing DoD network infrastructure the system must meet the DIACAP requirements which could take very long time to get a formal approval. However, Philips would seek DIACAP approval for a commercial Hybrid ILDC system which means in a real retrofit scenario the Hybrid ILDC will leverage the existing IT infrastructure for network connectivity. For instance, it would utilize the existing Ethernet LAN for network connectivity and IT servers for data logging thereby minimize the capital and labor costs. The prototype Hybrid ILDC system utilizes Tablet PCs as touch pad controllers. On the other hand commercial release will utilize an inexpensive touch pad controller. Also, the commercial deployments will be optimized to reduce the number of equipment deployed without compromising the performance. For example, the prototype system installed in Ft. Irwin has 9 zone controllers whereas a commercial deployment of similar area may need only one. Similarly, against 33 sensors currently mounted in the target area only 22 are actually needed. Furthermore, the mass produced commercial controllers and blinds will benefit from economies of scale to bring the costs significantly down. All these factors can significantly influence the life cycle cost of Hybrid ILDC system. Therefore, the cost-benefit analysis based on the prototype system costs would not be representative of expected cost-benefits to the DoD due to wide scale deployment

of the commercialized versions of the same technologies. To accurately project the expected cost-benefits to the DoD, costs of commercialized versions of the demonstrated technologies are derived. We have applied the best engineering judgment to derive these costs.

The OccuSwitch wireless and Dynalite are newly introduced commercial products. Hence, their capital costs are readily available for analysis. The installation and commission costs of commercial versions of these systems would be lower than those incurred at Ft. Irwin due to following reasons. 1) issues and complexities encountered during the pilot demonstration are resolved before the commercial product release, and, 2) installers and commissioners are already trained on the system. Better trained and well acquainted installers and commissioners would take less time and make fewer mistakes in installation and commissioning the system. In other words, as the number of deployment of these systems increases and they get more mature in the market the total system cost is expected to decrease from conservative to aggressive values as indicated in Tables 43, 44 and 45.

Similarly, planning costs for commercial system installations are significantly lower on account of following factors. 1) Knowledge, skills, insights and hands-on experience gained by planning team during this demonstration project have shortened the planning cycle and tended to avoid pitfalls, and, 2) planning tools, guidelines and software programs are available for commercial systems which reduces the time and efforts required to plan for a new project. To account for these improvements the training costs are excluded for commercial products. Furthermore, planning, installation and commissioning costs are scaled by an appropriate factor in the lifecycle cost, savings-to-investment ratio and payback time calculations.

In summary, the cost analysis assumes widespread deployment (at least few million sq ft) using commercial versions of these systems by the DoD. In this case, scale can allow for favorable pricing of material and labor and a more direct sales approach for the entire retrofit project including all aspects (material, installation and commissioning).

## 7.3 COST ESTIMATES

### 7.3.1 Estimated Investment

The best available estimates for the cost of technology in 2012 are used as inputs to derive the total investment in technology. Capital, installation and commissioning costs are added to compute total construction cost. On top of construction cost, 6% and 10% of total investment are added for SIOH (supervision, inspection and overhead) cost and design cost respectively as recommended by the NIST BLCC MILCON ECIP program to derive the first cost. We calculated the rebate offered by utility for upgrading the existing lighting system to a new lighting control system using the Lighting Rebate Catalog of SCE Company. Subtracting the utility rebate from the first cost results in net investment. These estimated costs for 3 technologies are listed in Table 37.

Below we compare the energy and maintenance costs of operating the legacy lighting system with those for upgraded lighting control system.

Table 37: Net investment in technology

| Cost Elements | Units | Hybrid ILDC | Dynalite | OccuSwitch |
|---|---|---|---|---|
| First cost (Design+ Capital+ Installation+ Commissioning+ SIOH) | $/sq ft | 6.7 | 5.04 | 4.14 |
| Utility rebate | $/sq ft | 1.05 | 0.5 | 0.75 |
| **Net Investment (First cost – Utility rebate)** | $/sq ft | 5.64 | 4.54 | 3.4 |

### 7.3.2 Estimated Energy Cost Saving

SCE's rate schedule GS-2 (non TOU) is used in Life Cycle Cost (LCC) analysis. This schedule has following main components:

- A monthly Customer Charge of $133.19/Meter/Month. We ignore this charge in our analysis.
- Energy Charges per kilowatt-hour (kWhr) consumed that vary by season. For summer season from June 1 to October 1, energy charges are $0.099/kWhr. For winter season from October 1 to June 1energy charges are $0.080/kWhr.

- Demand Charges consisting of Time-Related Demand and Facilities-Related Demand charges.
    - The Time-Related Demand Charge is applied only during SCE's summer season from June 1 to Oct 1. It is a per-kW charge applied to the greatest amount of registered demand in each summer season billing period. A time related demand charge of $19.26 is levied per kW per month during 4 months in summer.

    - The Facilities-related Demand Charge is also billed on a per-kW basis, yet it is in effect in each billing period throughout the year. It is applied to the greatest amount of registered demand in each billing period. A facility related demand charge of $12.25 is levied per kW per month throughout the year.

The annual electric energy costs for lighting are computed by applying the SCE's electric energy charges for summer and winter seasons to baseline and post retrofit energy consumption during summer and winter months respectively. Further energy cost savings are attained due to reduction in peak demand which is estimated based-on peak LPD reduction due to new system. Annual demand charges due to lighting are computed based on SCE's time related demand charges (for summer months) and facility related demand charges (throughout the year) to peak baseline and peak post-retrofit demands.

To estimate HVAC energy cost savings due to lighting upgrades we use the simulations results. Simulation results provide monthly heating and cooling loads for baseline and post-retrofit system configurations. We converted the cooling load into the electric energy consumed for cooling by dividing the cooling load with typical COP for HVAC system. In building 279, the

heating system is electric so the same process is applied to convert heating load into electric energy consumed for heating. On the other hand, in the building models representing buildings 602 and 279, the heating systems are gas based. For those buildings, the heating load is converted into natural gas consumption. The annual electric energy costs for HVAC are determined by applying the SCE's electric energy charges for summer and winter seasons to baseline and post retrofit electric energy consumption for HVAC during summer and winter months respectively. The commercial price of natural gas for the state of California was sourced from US Energy Information Administration which was $8.27/MCF in 2011.

Simulation results also provide the monthly peak heating (where applicable) and cooling loads which are converted into peak electricity demands by dividing the load with COP. Annual demand charges due to HVAC are computed by applying SCE's time related demand charges (for summer months) and facility related demand charges (throughout the year) to peak baseline and peak post-retrofit demands. In buildings where the heating systems are gas based, the demand charges do not apply.

Aggregate annual energy costs are sum of electric energy charges (for lighting and HVAC), the demand charges (for lighting and HVAC) and natural gas costs.

### 7.3.3 Estimated Maintenance Cost Savings

The Hybrid ILDC and OccuSwitch systems have battery powered sensors. Since the batteries of the sensors would need replacements, the replacement costs have to be accounted in the lifecycle cost calculations. Battery replacement costs are estimated based on lifetime of the battery(10 years), labor cost for replacement ($3.0 per battery for group replacement), material cost of the battery ($6.0 each) and battery deployment density (1 battery per 94 sq ft).

Lamp replacement costs are not included in the life-cycle cost calculations for the following reasons. Lamp types and lamp counts in pre-retrofit and post retrofit systems are comparable. Although the operating hours may have changed from the pre-retrofit to post retrofit scenario, the data on lamp operating hours is not available to gauge its impact on replacement cycle. In the absence of this information it is reasonable to assume that the cost of replacing the lamps is more or less the same in both scenarios. Presuming that lamp replacement costs are identical in both the scenario, they are excluded from lifecycle cost calculations. The remote metering, monitoring, and management capabilities of the lighting control system provide maintenance cost savings which are not included in this analysis. Furthermore, non-tangible benefits such as occupant comfort and productivity increase will also be realized.

## 7.4 COST DRIVERS

Following are the main cost drivers.

The sophisticated systems (e.g. Hybrid ILDC and Dynalite) are more cost-effective in large installations for the following reasons. The cost of special equipment (e.g. central server) and software (e.g. database software and energy management software) get amortized over a large area. Similarly, design, installation, commissioning, supervision, inspection and overhead costs

are apportioned over a larger floor space. Due to these economies of scale, the total investment per sq ft reduces as coverage area increases.

The cost of installation, commissioning, supervision and inspection are sensitive to local labor rate at target site. These costs will also vary depending on whether unionized or non-unionized labor is used. Some DoD sites may have a limited pool of electrical contractors that are authorized to perform work at these sites could lead to higher costs.

The cost of electric energy significantly varies regionally. Energy costs play a significant role in payback time and savings to investment ratio computation. Higher energy costs lead to shorter payback time and vice versa.

Typically, Utilities offer many different rate structures. Utility rates also vary based on time-of-use (e.g. On-Peak, Mid-Peak and Off-Peak conditions) and seasonally (summer schedule versus winter schedule). These factors influence return-on-investment and have to be analyzed on a case by case basis.

The Utility rebates vary based on the type of control system. Some utilities provide rebates based on the quantity of control equipment, such as occupancy sensors and photo-sensors. On the other hand other utilities offer rebates based on the reduction in LPD.

Several factors influence energy savings potential of a lighting control system such as building type, orientation, window to wall ratio, daylight availability, surrounding environment, daylight penetration, climate conditions, usage pattern, occupancy profile, type and efficiency of light sources, layout of lighting equipment and like. Hence, it is not straightforward to estimate energy savings potential of a lighting control system. An in-depth analysis using sophisticated energy modeling tools (e.g. EnergyPlus) may be required to gauge the expected energy savings due to the advanced lighting control system.

The Hybrid ILDC system not only saves lighting energy but also HVAC energy by regulating the admission of solar heat gain. The impact of integrated lighting and shading control system on HVAC energy consumption depends upon window-to-wall ratio, orientation of windows, climate conditions, solar irradiance patterns, type of HVAC system, reflectivity of blinds, location of blinds (external v/s internal) and control strategies implemented. In general, the HVAC cost savings due lighting controls are higher in warmer climates where cooling energy dominates. Whole building energy modeling tools such as EnergyPlus may also be helpful in estimating the HVAC energy savings due to lighting system upgrades.

## 7.5 COST ANALYSIS AND COMPARISON

The cost analysis was performed using the Building Life-Cycle Cost Program (BLCC5). BLCC5 is a software program developed by the National Institute of Standards and Technology (NIST) for the economic analysis of energy and water conservation and renewable energy projects in buildings. Besides life-cycle costs, BLCC5 can also compute other economic measures such as net savings, savings-to-investment ratio, adjusted internal rate of return, and years to payback.

To illustrate how the size of the installation impacts the cost benefit trade-offs for each technology, we define 3 different deployment categories based on the floor area covered per deployment. A small deployment is defined as a deployment with total floor area of less than or equal to 50,000 sq ft. A medium deployment is defined as a deployment with coverage area between 50,000 and 200,000 sq ft. A large deployment is defined as a deployment with coverage area more than 200,000 sq ft.

Table 38: Cost assumptions for 3 deployment categories for OccuSwitch Wireless systems

| | **Small deployment (Ft. Irwin)** | **Medium deployment** | **Large deployment** |
|---|---|---|---|
| Coverage Area | <=50,000 sq ft | >50,000 and <=200,000 sq ft | >200,000 sq ft |
| Design costs | 100% | 85% | 70% |
| Total material costs for equipment | 100% | 70% | 50% |
| Installation and commissioning costs | 100% | 70% | 40% |
| Supervision, inspection, overhead costs | 100% | 85% | 70% |
| Utility rebate | 100% | 100% | 100% |
| Battery replacement costs | 100% | 95% | 90% |

Table 39: Cost assumptions for 3 deployment categories for Dynalite system

| | **Small deployment (Ft. Irwin)** | **Medium deployment** | **Large deployment** |
|---|---|---|---|
| Coverage Area | <=50,000 sq ft | >50,000 and <=200,000 sq ft | >200,000 sq ft |
| Design costs | 100% | 85% | 70% |
| Total material costs for equipment | 100% | 60% | 40% |
| Installation and commissioning costs | 100% | 70% | 55% |
| Supervision, inspection, overhead costs | 100% | 85% | 70% |
| Utility rebate | 100% | 100% | 100% |
| Battery replacement costs | 100% | 95% | 90% |

Table 40: Cost assumptions for 3 deployment categories for Hybrid ILDC system

| | Small deployment (Ft. Irwin) | Medium deployment | Large deployment |
|---|---|---|---|
| Coverage Area | <=50,000 sq ft | >50,000 and <=200,000 sq ft | >200,000 sq ft |
| Design costs | 100% | 85% | 70% |
| Total material costs for equipment | 100% | 65% | 55% |
| Installation and commissioning costs | 100% | 65% | 55% |
| Supervision, inspection, overhead costs | 100% | 85% | 70% |
| Utility rebate | 100% | 100% | 100% |
| Battery replacement costs | 100% | 95% | 90% |

Based on the coverage area, the 3 systems deployed at Ft. Irwin fall under the category of small deployment. Due to economies of scale principles, the cost per sq ft for large deployment is expected to be lower than that for small deployments. To derive costs for medium and large deployments the results from Ft. Irwin are scaled based on the best engineering judgment and in-house data from other commercial projects. As shown in Table 38, Table 39 and Table 40 the Ft. Irwin cost ($/sq ft) estimates are scaled by assumed weighting parameters to derive the cost elements ($/sq ft) for medium and large deployments.

Table 41: Energy and demand cost and savings assumptions for 3 implementation scenarios

| | Conservative | Typical (Ft. Irwin) | Aggressive |
|---|---|---|---|
| Electric Energy Charges | 75% | 100% | 125% |
| Demand charges | 75% | 100% | 125% |
| Lighting energy Savings | 80% | 100% | 120% |
| Lighting demand savings | 90% | 100% | 110% |
| HVAC Energy Savings | 80 | 100% | 120% |
| HVAC demand savings | 90% | 100% | 110% |

The cost-benefit tradeoffs of a given technology are also influenced by several other factors such as the cost of energy, specific characteristics of the building, climate conditions, usage patterns and occupancy profile. To account for these variations we define three implementation scenarios. We consider the Ft. Irwin deployment as a typical implementation scenario. We define a conservative implementation scenario by scaling down the energy charges, demand

charges and energy savings by factors indicated in Table 41. The conservative scenario captures unfavorable settings where energy costs and savings are significantly lower than Ft. Irwin scenario. On the other hand an aggressive scenario represents the situation where energy costs and savings are higher than Ft. Irwin scenario.

Above mentioned cost data were fed to BLCC5 MILCOM ECIP module. NIST recommended real discount rate of 3% was provided as input to the program. California was selected as site location and commercial electricity rate schedule was selected as input. BLCC5 applied DoE's electrical energy escalation rate schedule built in the program to derive the payback time and SIR.

Table 42, Table 43 and Table 44 summarize the economic benefits of retrofitting the existing lighting systems with the Hybrid ILDC, OccuSwitch and Dynalite respectively. The results are derived using NIST BLCC MILCON ECIP program. The results are presented for 3 deployment categories defined in Table 38 for 3 scenarios defined in Table 41. The results in the row typical and in the column small deployment captures the cost-effectiveness of the system in Ft. Irwin. These tables show the wide spectrum of outcomes that are expected in commercial deployments.

In general, cost effectiveness of the lighting control systems depend on the size or coverage area of the implementation, since control hardware is amortized over the entire area. Typically, with networked lighting controls solutions such as Dynalite and Hybrid ILDC, the central control server and associated software are costly elements that weigh heavily in smaller size deployments. Consequently it can be seen in Table 42, Table 43 and Table 44 that cost objectives (i.e., payback period < 7 yrs and SIR>2) are more readily met for medium and large size deployments and with aggressive energy and demand savings for smaller size deployments. Each system is unique and suitable for specific building types. For example it can be seen that the OccuSwitch system due to its room or zone based control architecture is more cost effective for smaller size deployments compared to the others. Furthermore, for all the technologies demonstrated, the cost per unit area is expected to decrease as system deployments increase or as the systems get more mature. In the initial deployment phase costs are conservative or high and as they become more mature the cost can be more aggressive as shown in Table 42, Table 43 and Table 44.

Overall it can be stated that for medium and large deployments as technologies gain maturity cost objectives will be met.

Table 42: Cost-effectiveness results for Hyrbid ILDC for 3 deployment categories under 3 implementation scenarios

| | Small deployment | | Medium deployment | | Large deployment | |
|---|---|---|---|---|---|---|
| Net Investment $/sq ft | 5.64 | | 3.51 | | 2.79 | |
| | Simple Payback time (yrs) | SIR over a 20 year period | Simple Payback time (yrs) | SIR over 20 a year period | Simple Payback time (yrs) | SIR over a 20 year period |
| Conservative | 9.85 | 1.00 | 6.13 | 1.80 | 4.87 | 2.20 |
| Typical | 6.25 | 1.60 | 3.89 | 2.80 | 3.09 | 3.40 |
| Aggressive | 4.33 | 2.40 | 2.69 | 4.00 | 2.14 | 5.00 |

Table 43: Cost-effectiveness results for OccuSwitch for 3 deployment categories under 3 implementation scenarios

| | Small deployment | | Medium deployment | | Large deployment | |
|---|---|---|---|---|---|---|
| Net Investment $/sq ft | 3.40 | | 2.25 | | 1.44 | |
| | Simple Payback time (yrs) | SIR over a 20 year period | Simple Payback time (yrs) | SIR over a 20 year period | Simple Payback time (yrs) | SIR over a 20 year period |
| Conservative | 8.52 | 1.20 | 5.65 | 1.80 | 3.61 | 2.80 |
| Typical | 5.37 | 1.80 | 3.56 | 2.80 | 2.28 | 4.40 |
| Aggressive | 3.71 | 2.60 | 2.46 | 4.00 | 1.57 | 6.20 |

Table 44: Cost-effectiveness results for Dynalite for 3 deployment categories under 3 implementation scenarios

| | Small deployment | | Medium deployment | | Large deployment | |
|---|---|---|---|---|---|---|
| Net Investment $/sq ft | 4.54 | | 3.39 | | 2.25 | |
| | Simple Payback time (yrs) | SIR over a 20 year period | Simple Payback time (yrs) | SIR over a 20 year period | Simple Payback time (yrs) | SIR over a 20 year period |
| Conservative | 13.55 | 0.80 | 10.12 | 1.00 | 6.70 | 1.40 |
| Typical | 8.67 | 1.20 | 6.47 | 1.60 | 4.29 | 2.40 |
| Aggressive | 6.05 | 1.60 | 4.51 | 2.20 | 2.99 | 3.40 |

# 8 IMPLEMENTATION ISSUES

This project afforded numerous learning opportunities. As the first ESTCP project in lighting controls at Fort Irwin the project team had to explore new ways of working to optimize total value. Certain constraints had to be addressed that are unique perhaps to DoD facilities. For instance, all retrofit work had to be carried out during after-hours, weekends and holidays with escorts from DoD that needed to be scheduled in advance. This was a challenge as relevant building contact persons were not readily available. Each building manager had to be contacted to set up work schedules. During the early phase of the project the process of getting procedural information was slow. Effective method of communication (E-mails, phone, voice messages etc.) with relevant base personnel varied from case to case. After the initial phase a point contact suggested by DPW was helpful.

Lessons learned from these demonstrations and issues encountered are summarized in this section to aid in the future implementation of the technologies.

## 8.1 Buy-in from stakeholders

Securing the support of all the stakeholders early on is vital to the success of the project. Specifically, continued support from the DPW staff throughout project is essential for timely execution of the demonstration project. Presenting the objectives of the project and how they relate to DoD’s energy security goals to senior leaders (e.g. Garrison Commander, Director of DPW, etc) can help. Educating the building occupants about the benefits of the technology can also help in accelerating the adoption of new technology. Consulting information assurance manager and privacy officer during the planning phase and configuring systems to address their concerns can help mitigate any potential issues related to security and privacy.

## 8.2 Addressing DPW concerns

Articulating the goals of the project and how they align with the mission of DPW is important to get them excited. Defining the scope of work and roles of DPW staff is essential to manage the expectations. A point of contact for communications and approvals should be established to streamline the execution. Promptly addressing the concerns of DPW is crucial for their continued support. Potential concerns such as reimbursement for the time spent by DPW staff and warranty of installed systems should be discussed. The processes and responsibilities for maintaining the demonstration equipment during and after the execution of the project should be agreed with DPW. Agreement should include the service contact information, reporting and response time expectations and service dispatch processes. If relevant, decommissioning and disposal of demonstration equipment should also be discussed.

## 8.3 Establishing the channel for communication

A clear communication channel should be established with the base to communicate any issues, concerns, occupant complaints or system faults back to project team in a timely fashion. Lack of coordination can hold up tasks and caused delays. Project team explored the possibility of defining a role of project coordinator and reimbursing the coordinator from project’s budget but

that idea was not pursued further by the base. A formal role of coordinator and reimbursement for coordinator's services should be discussed with concerned parties at the base.

Note that the process for gathering user feedback is dependent entirely on the key contact at the installation site who alone can administer the process of handing out questionnaire and ensuring response, for reasons of anonymity and thoroughness. In this project our key contact in DPW was unable to solicit response from the majority of the occupants of the new lighting systems in spite of repeated requests from the project team. This has limited the project team's ability to draw statistically significant conclusions for the study as far as occupant satisfaction is concerned. Perhaps the project ambitions were unrealistic in this respect.

If required, the host site should also be willing to provide access to the building during off hours, nights and weekends. Electrical contractors hired for installation and commissioning should be able to gain access to the facilities. On-site support may be needed to receive and store equipment, supplies and spares.

### 8.4 Addressing regulatory issues

Advanced planning to comply with regulatory requirements will help avoid any delays due to regulatory approvals. Requirements for DoD Information Assurance Certification and Accreditation Process (DIACAP) should be investigated early on. Certification requirements need to be clarified with the base so that valuable benefits of energy savings measures can be realized efficiently and effectively. If applicable, the DIACP approvals or waivers should be secured. Similarly, compliance to privacy policies should be ensured. Other contractual obligations that may impact project planning (e.g. small business subcontracting plan), execution (e.g. managing government property) and procurement (Buy American Provision of the American recovery and investment act) should also be factored into overall planning.

### 8.5 Overcoming barriers to adoption

Energy efficiency is the key motivator for adopting advanced lighting controls. Other factors such as user satisfaction, occupant comfort and productivity enhancement are important, however, not well recognized. More awareness about these factors among decision makers is needed. Presenting them the true costs and benefits of various technology options can accelerate adoption of these technologies.

DPW and other organizations responsible for maintaining the lighting systems are concerned about staff training and resources needed to maintain such advanced control systems. This sometimes dampens the enthusiasm for advanced control systems. This needs to be addressed broadly in DoD to benefit from the significant savings in cost and energy. Control systems with remote monitoring and automated fault detection, diagnosis and recovery features can address some of these concerns. Integration with other building systems via a hub is an option that should be further explored. Demonstration projects such as this one which prove reliability and maintainability of advanced controls can help mitigate those concerns and accelerate the adoption. Maintenance contracts can be included in the procurement processes to ease the burden on local maintenance staff.

Wireless controls are sometimes perceived as unreliable. In this project, no issues related to reliability of wireless controls were observed. More demonstrations of wireless controls in DoD settings can help overcome the perception and boost the credibility of wireless controls.

## 8.6 Field demonstration issues

### 8.6.1 OccuSwitch in building 602

In building 602 the OccuSwitch system had performed as intended; however, there were a few maintenance issues. The local contractor hired for the job did not follow the wiring instructions which lead to some wiring errors and consequent malfunction and user dissatisfaction. Ballasts had to be rewired to correct this.

Soon after the retrofit, the building manager reported a perceived delay in turning lights on in a restroom. This issue was resolved by replacing the programmed start ballasts in the restroom with instant start ballasts, which reduced the delay but sacrificed dimming capabilities in the restrooms. The building manager was satisfied with the response time after the replacement.

Another issue encountered in building 602 was caused by malfunctioning amplifiers. Amplifiers are not part of OccuSwitch system however, third party amplifiers were installed in the open plan office area to extend the range of dimming signals to support a large number of fixtures. Although the OccuSwitch system was operating properly, malfunctioning amplifiers prevented it from dimming some of the lights in open plan area. Once the amplifiers were replaced, the lights started performing as intended.

Finally, in the OccuSwitch system demonstrated in building 602, user selected dimming levels reset to default levels each time the space becomes unoccupied. Based on feedback from occupants, Philips developed a software upgrade that stores user preferred dimming level as the new default, thereby setting lights to their most recently selected level the next time a space is occupied.

OccuSwitch system demonstrated in Building 602 is an engineering sample meant for field tests so some issues are expected. In the commercial product these issues have been fixed.

### 8.6.2 Hybrid ILDC in building 279

Hybrid ILDC supports blind slat angle control based on HVAC mode to optimize energy in an unoccupied state. However, this feature was not enabled at Fort Irwin due to lack of integration with the HVAC system.

Hybrid ILDC is an experimental system made from COTS components. It utilized a touch screen Tablet for user interface. These tablets run a Windows operating system which occasionally crashed. Tablets were scheduled to auto-reboot once a week. On a couple of occasions some tablets failed to boot properly after the scheduled shutdown. These issues were promptly resolved by team.

In response to a question asking if they had concerns that problems could have come up during the installation process of Hybrid ILDC system in building 279, one installer disagreed and one agreed, citing concerns that they only received one step of instructions at a time in that building, which prevented them from planning their work there as effectively as possible. Since Hybrid ILDC is a research prototype custom designed and developed for the demonstration, detailed installation instruction manuals are not available. Nevertheless, a commercial version of Hybrid ILDC system will have a streamlined installation process outlined in an installation manual to aid planning and execution.

#### 8.6.3 Dynalite in building 988

Three ballasts were replaced in study area without the knowledge of project team. Since the new ballasts were not configured to receive control system commands they did not respond to the control messages. This lead to some lights remaining on 24 hours/day for about 14 days until the issue was discovered by the project team and ballasts were configured to receive control system commands.

### 8.7 User satisfaction survey

DPW was only able to identify four occupants for the user satisfaction survey in building 279 during both the pre-retrofit and post-retrofit study periods. Out of 4 occupants who were sent survey questionnaires, one person responded to the survey during the pre-retrofit period, and two responded during the post-retrofit period. In building 988, only 4 out of 8 occupants responded to the pre-retrofit survey, and only 1 out of 9 responded to the post-retrofit survey. DPW did not send a reminder email to the post-retrofit occupants out of concern about disturbing them. The extremely low number of people surveyed limited the extent to which results can be considered representative.

### 8.8 Procurement

Philips Lighting is one of the largest manufacturers of commercial lighting products in the U.S; and its control unit provides a complete line of commercial lighting control products. Hybrid ILDC system is a research prototype. Some components of the technology (e.g. wireless sensor packages) are commercially available. Commercialization prospects of the system solution are being evaluated based on market research and performance results from in-house trials. Since the demonstrated technology leverages standardized protocols (e.g. ZigBee/IP), COTS components (e.g. Ethernet/SSLs) and open source software (e.g. MySQL); it benefits from economies of scale, availability of skilled manpower and compatibility with existing IT infrastructure thereby enabling easier productization and quicker market adoption.
Dynalite and OccuSwitch systems are commercially available now.

Philips already possesses a broad distributor network that sells to both commercial and governmental entities including DoD. Philips offers its products as systems and components, and sells them primarily to OEMS, distributors and system integrators/VARs that provide turnkey installations to end users, including DoD bases. Philips has worked with many DoD installations to deploy commercial advanced lighting technologies. Since this project was

initiated, the Dynalite has been installed at several sites in US including some in DoD (e.g. Ft. Bliss). In support of its commercially released products, Philips provides technical specifications, data sheets, installation guides, quick-setup instructions, web casts, seminars and workshops. Also provided for commercial products are training (for installers, distributors, specifiers and end users), commissioning (including system programming and configuration), warranty, technical support, diagnostics, field upgrades, continuing education and new technology updates. Listing on GSA schedules will be sought in order to facilitate acquisition of the systems and components at privileged pricing.

The Dyanlite system, based on robust wired communication links, is optimized for new constructions or deep retrofit where the incremental cost of wiring is minimal since it can be done during and together with the wiring of the rest of buildings. However, as shown in this demonstration project, the system can be effectively implemented in building with drop ceilings as well.

The OccuSwitch and the Hybrid ILDC system employing wireless RF communication links are meant to be flexible and cost effective for light retrofit in addition to new constructions and deep retrofit. The OccuSwitch system, with its modular room based or area based control is suitable for small buildings where full networking is not required. The Hybrid ILDC as well as the Dynalite systems are most appropriate in large buildings where centralized monitoring and controls create value by allowing features such as demand response or peak load control.
Based on the information and learning from the Fort Irwin project alone it is not possible to draw conclusions on requirements for military buildings as a whole as it pertains to lighting code. However, certain administrative office buildings that are used in ways similar to those with commercial buildings, the standard lighting codes should be applicable.

### 8.9 Post-demonstration system transition to Ft. Irwin

It has been mutually agreed to decommission all the three systems at the end of the project. The ILDC system is a research prototype and is not commercially available at this time, and the decommissioning of this advanced system is in line with our original plan.

While the commercially available Dynalite system met all the performance criteria for energy savings and user satisfaction, it was mentioned by DPW that unfamiliarity with maintenance related aspects of networked lighting control system was a barrier to acceptance. This needs to be brought up to appropriate administration levels to come to a formal policy. To maintain consistency in approach, it was mutually agreed to decommission the OccuSwitch Wireless system from building 602.

### 8.10 System integration with local LAN and building management systems

In general standalone systems can be installed independent on the local LAN as done in the project. Integration with the local LAN will require agreement and Certification such as DIACAP. Integration with BMS can be accomplished via RS232, BacNet or LONWORKS among others.

For the networked lighting control systems demonstrated, the Dynalite systems is available as a commercial product. This system can be either operated as a standalone system side by side with building energy management systems or integrated with them using gateways that are available with the system. Currently integration devices in the form of gateways are available for the following, among others, for interfacing with Building Energy management systems and other systems. Details are available in: http://www.lighting.philips.com/pwc_li/main/subsites/dynalite/products/assets/pdf/integration_devices_60-69.pdf

- Ethernet (DAC100BT). The device supports the TCP/IP protocol, with static or DHCP assigned IP addressing. Routing Mode links multiple DAC100BTs together in point-to-point or broadcast modes. An integral webserver allows browser-based control scenarios. The interface incorporates a Programmable Logic Controller that can process comprehensive conditional and sequential logic and arithmetic functions. The DAC100BT is also capable of routing DyNet to third-party systems, such as audio-visual and building automation systems, providing an integrated approach to total building control and energy management. Key features include OLED panel display highlighting panel status, along with local area overrides, integrated user front panel and a range of test buttons and maintenance switch indicators. A mechanical key lock is provided for secure access.

- RS232 (DNG232/ DDNG232/DMNG232). The Philips Dynalite 232 <-> 485 gateway range is designed to enable cost-effective serial port integration between the Philips Dynalite control system and third-party systems such as AV systems, lighting desks, data projectors, HVAC, BMS and security systems.

- DDNG485 Network Gateway. The Philips Dynalite DDNG485 is a flexible network communications gateway designed for DyNet RS485 networks. The two opto-isolated RS485 ports enable the DDNG485 to implement a trunk and spur topology on large project sites, with the device providing a high-speed backbone opto-coupled to many lower speed spurs.

- DDNG-LON LON Gateway. The DDNG-LON is designed to provide a LON single point gateway to a Philips Dynalite control system. The DDNG-LON is based on Echelon Corporation's Neuron 3120 chip, which supports 63 SNVT's and will support preset control of 100 presets per area for 30 areas. Multiple DDNG-LON devices can be cascaded together to accommodate larger or more complex DyNet networks. The device is configured to operate on the LON network with Echelon Corporation's LonMaker.

- DDNG-BACnet BACnet Gateway. The DDNG-BACnet allows for high level integration between the Philips Dynalite system and BMS using the BACnet protocol. This gateway between the two systems allows high level communication, opening up a number of integration opportunities. When using the DDNG-BACnet gateway, the BMS systems can trigger tasks and timed based events and the Philips Dynalite system can report back current system statuses. This Philips Dynalite gateway can support 1000 BACnet addressable points that can be adjusted by either system for full transparency of communications.

## 8.11 Baseline for energy performance comparison

DoD needs to set the guidelines for selecting the baseline for energy performance comparison. One option is to select the baseline based on the code requirements that were in effect when the building was constructed or lighting system was last upgraded. Another option is to meter the lighting energy consumption for some duration and use the metered data as the baseline. Although metering is more accurate than code baseline, instrumenting the whole building for circuit by circuit lighting energy consumption metering can be very expensive. One way to reduce the cost is to instrument a representative section of the building and then extrapolate the data to the entire building.

Yet another option is to use battery operated portable light loggers to log lighting usage and then estimate the lighting energy consumption based on the installed lighting power density. Portable light loggers can be installed by anyone whereas the high voltage current/energy meters can only be installed by licensed electricians. Hence, portable light loggers can be less accurate but more cost-effective solution for lighting energy auditing compared to current/energy meters. Nevertheless, the length of study duration should be long enough to capture the seasonal variations and occupancy dynamics.

## 8.12 Cost evolution of the solutions

With advanced networked lighting control systems the major initial cost components of the solution include, subsystem devices or components and installation and commissioning. Each of these cost elements decrease in size as the systems become more mature. As the applications grow in volume, economies of scale help to reduce the initial hardware/firmware unit cost. Additionally, R&D effort in systems architecture, systems integration and commissioning techniques provide cost reduction paths for new solutions.

Installation and commissioning costs are functions of connectivity technologies deployed in the system operation and control. Wireless technologies and existing IP based connectivity help to minimize installation costs to a large extent. Furthermore, as installers get trained with the systems, installation related cost decrease.

# APPENDICES

## Appendix A: References


[1] EIA, Commercial Buildings Energy Consumption Survey, 2003, Table E3.

[2] Akbari, H. and Konopacki, S. "*End-use energy characterization and conservation potentials at DoD Facilities: An analysis of electricity use at Fort Hood, Texas"*, DoE Contract # AC03-76SF00098, LBL Report #36974.

[3] ZigBee Alliance, "*ZigBee specification*", ZigBee document number 054024r01 (ZigBee-2006 specification), December 2006

[4] IEEE *802.15.4 Standard: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rates Wireless Personal Area Networks (LR-WPANs*), IEEE Press, New-York 2003.

[5] ZigBee Alliance, "*ZigBee-PRO Stack Profile: Platform restrictions for compliant platform testing and interoperability*", document number 074855r04, October 2007

[6] ZigBee Alliance, "*Home Automation profile specification. ZigBee profile 0x0104*", document number 053520r16, August 2007.

[7] US Environmental Protection Agency, eGRID2010 Version 1.1 Year 2007 GHG Annual Output Emission Rates, http://www.epa.gov/egrid, 2010

[8] Amy Rushing, Joshua D. Kneifel and Barbara C. Lippiatt, "*Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis, Annual Supplement to Handbook 135*" NISTIR 85-3273-25. National Institute of Standards and Technology, May 2010.

[9] Joy Wei, Abby Enscoe and Francis Rubinstein, "*Responsive Lighting Solutions*," Final Report to U.S. General Services Administration, September 2012.

## Appendix B: Management and Staffing

| POINT OF CONTACT<br>Name | ORGANIZATION<br>Name<br>Address | Phone<br>Fax<br>E-mail | Role in Project |
|---|---|---|---|
| Dr. Jim Galvin | SERDP/ESTCP<br>901 North Stuart Street, Suite 303<br>Arlington, VA 22203 | (703) 696-2121<br>(703) 696-2114<br>James.Galvin@osd.mil | Energy & Water Program Manager |
| Mr. John Thigpen, | ESTCP<br>901 North Stuart Street, Suite 303<br>Arlington, VA 22203 | (703) 326-7822<br>(703) 696-2114<br>jthigpen@hgl.com | Energy & Water Program Manager Assistant |
| Mr. Bobby Khaksari | HydroGeoLogic, Inc.<br>11107 Sunset Hills Road, Suite 400<br>Reston, VA 20190 | (703) 736-4539<br>rkhaksari@hgl.com | Energy & Water Program Manager Assistant |
| Satyen Mukherjee | Philips Research N. A.<br>345 Scarborough Road Briarcliff Manor NY 10510 | (914) 945-6320<br>(914)-945-6014<br>Satyen.mukherjee@philips.com | Principle Investigator |
| Sree Venkit | Philips Lighting Electronics N.A.<br>10275 West Higgins Road Rosemont, IL 60018 | (847) 390.5070<br>(847) 390 5264<br>sree.venkit@philips.com | Performer |
| Francis Rubinstein | Lawrence Berkeley National Laboratory<br>One Cyclotron Rd, Berkeley, CA 94720 | FMRubinstein@lbl.gov | Performer |
| Muhammad Bari | Directorate of Public Works<br>Fort Irwin, CA 92310-5097 | (760) 380-3655<br>(760) 964-1636<br>muhammad.bari@us.army.mil | Ft. Irwin Liaison |
| Dagnachew Birru | Philips Research N. A.<br>345 Scarborough Road Briarcliff Manor NY 10510 | (914) 945-6401<br>(914) 945-6330<br>dagnachew.birru@philips.com | Performer |
| Maulin Patel | Philips Research N. A.<br>345 Scarborough Road Briarcliff Manor NY 10510 | (914) 945-6156<br>(914) 945-6156<br>Maulin.patel@philips.com | Performer |

| | | | |
|---|---|---|---|
| Matthew Helm | Philips Lighting Electronics N.A. 10275 West Higgins Road, Rosemont, IL 60018 | (847) 390.5117<br>matt.helm@philips.com | Performer |
| Osvaldo Velarde | Philips Control Systems and Solutions 13560 Morris Road Alpharetta, GA 30004 | (770) 510-1370<br>(915) 449-5991<br>osvaldo.velarde@philips.com | Project coordinator |
| James Schmidt | Philips Research N. A. 345 Scarborough Road Briarcliff Manor NY 10510 | (914) 945-6394<br>(914) 945-6330<br>j.schmidt@philips.com | Advisor |

## Appendix C: Adjusted Baselines

In order to compensate for the fact that installed lighting power densities for the measured circuits in Buildings 602 and 988 were changed when the lighting controls were installed, the team adjusted the measured baseline usage data as shown in the tables below. As shown, the measured pre-retrofit LPDs were adjusted either up or down on a per circuit basis to match the "pre-retrofit" LPD to the LPD that was actually installed as a result of the retrofit. Note that the use of an adjusted baseline means that any measured energy savings is attributable only to the lighting controls and not due to any changes because of the lighting re-design.

Another way to adjust the pre-retrofit lighting LPDs would be to use measured illuminances pre- and post-installation. However, this is a much less precise method than adjusting based on power.

Adjustment factor calculations in building 602:

| Circuit | Pre-retrofit installed W | Post-retrofit installed W | Factor |
|---|---|---|---|
| 18 | 892 | 612 | 0.686 |
| 20 | 785 | 612 | 0.779 |
| 22 | 881 | 748 | 0.849 |
| 28 | 433 | 408 | 0.943 |
| 30 | 937 | 1020 | 1.088 |
| 32 | 1490 | 1020 | 0.685 |
| 34 | 421 | 680 | 1.613 |
| 36 | 436 | 952 | 2.185 |
| 38 | 630 | 816 | 1.294 |

Adjustment factor calculations in building 988:

| Circuit | Pre-retrofit installed W | Post-retrofit installed W | Factor |
|---|---|---|---|
| 4 | 1173 | 2121 | 1.808 |
| 6 | 990 | 1111 | 1.122 |
| 14 | 1710 | 1919 | 1.122 |
| 16 | 1074 | 1228 | 1.143 |
| 25 | 1770 | 3030 | 1.712 |

# Appendix D: Non-lighting Loads

Constant non-lighting loads were determined to be on three circuits in building 988. As a result, constant current values were subtracted from CT readings on these circuits prior to analysis, during both the pre-retrofit and post-retrofit periods. These were:

| Circuit | Subtracted current (A) |
|---:|---:|
| 4 | 0.68 |
| 6 | 1.59 |
| 14 | 1.25 |

# Appendix E: Energy analysis for additional post-retrofit periods

1. Energy Performance Of OccuSwitch In Building 602 During Additional Post-retrofit Periods

To analyze the energy and demand performance of the OccuSwitch system installed in Building 602, a total of four discrete data sets were examined. The time intervals for the different test periods, the total number of days analyzed and the number of weekdays, weekends and holidays is given in Table 45.

Table 45: Number of days analyzed during pre-retrofit and post-retrofit periods

| | *Number of Days Analyzed Over Course of Testing in Building 602* | | | | | |
|---|---|---|---|---|---|---|
| Test Period | Start | Stop | Total Days | Weekdays | Weekend Days | Holidays |
| Pre-retrofit | 9/16/2010 | 1/7/2011 | 71 | 44 | 21 | 6 |
| Post-retrofit 1 | 5/7/2011 | 12/23/2011 | 120 | 83 | 33 | 4 |
| Post-retrofit 2 | 1/3/2012 | 7/15/2012 | 176 | 123 | 49 | 4 |
| OccuSwitch Rev | 7/27/2012 | 9/26/2012 | 62 | 43 | 18 | 1 |

The post-retrofit period 1 dataset used in analysis consists of 120 days made up of 83 weekdays, 33 weekend days, and 4 holidays that were recorded from May to December 2011. This dataset included fewer days than the targeted six months of post-retrofit data due to a hardware failure caused by a lightning storm that could not be quickly resolved because of visitation restrictions. However, since seasonal trending associated with daylight availability did not appear to be a factor in this building, this dataset is believed to be sufficient for robust annual energy use estimates.

The post-retrofit period 2 dataset ran from Jan 2012 until July 25, 2012. Note that OccuSwitch firmware was upgraded on July 26, 2012 to fix some of the issues observed earlier in the demonstration. The final test period, Post OccuSwitch Revision period, was used to estimate any changes in system performance caused by the firmware upgrade.

1.1. Reduce lighting demand

Peak LPD was calculated for each week of data collected. No outliers were identified for either the pre-retrofit or the post-retrofit data. These datasets included a peak pre-retrofit metered LPD of 1.14 W/sq ft and a peak adjusted pre-retrofit LPD of 1.17 W/sq ft. The peak post-retrofit LPD over a 15 minute interval was 0.96 W/sq ft, 0.94 W/sq ft, and 0.95 W/sq ft for post-retrofit periods 1, 2, and OccuSwitch Rev (Table 46).

The goal was to demonstrate at least a 25% reduction in peak LPD compared to code baseline. The results show 47-48% savings compared to the code baseline during the additional post-retrofit periods, substantially exceeding the target.

Table 46: Building 602 peak LPD results

| | | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline | Post-retrofit Period | | |
|---|---|---|---|---|---|---|---|
| | | | | | Period 1 | Period 2 | OccuSwitch Rev |
| | Peak LPD over a 15 minute period (W/sq ft) | 1.14 | 1.17 | 1.81 | 0.96 | 0.94 | 0.95 |
| % savings compared to | Pre-retrofit metered | - | - | - | 16% | 18% | 17% |
| | Adjusted pre-retrofit | - | - | - | 18% | 20% | 19% |
| | Code baseline | - | - | - | 47% | 48% | 48% |

The figures below present cumulative occurrences of weekday daily peak LPDs for each circuit in Building 602. The pre-retrofit metering period included 44 weekdays while the post-retrofit metering periods 1, 2, and 3 (OccuSwitch Rev period) included 83, 123, and 44 weekdays, respectively.

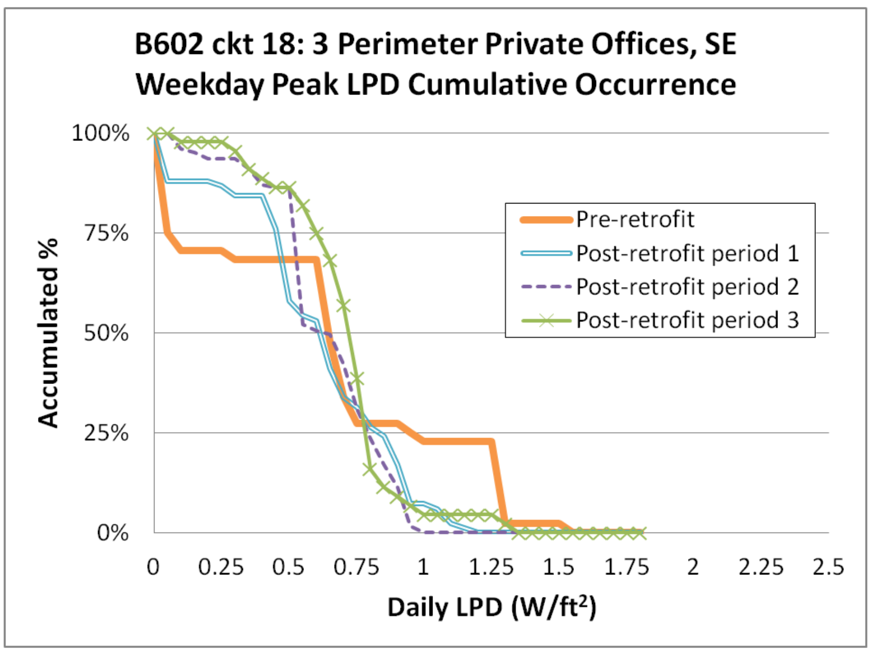



Figure 48: Building 602 Circuit 18 weekday peak lighting power density (LPD)

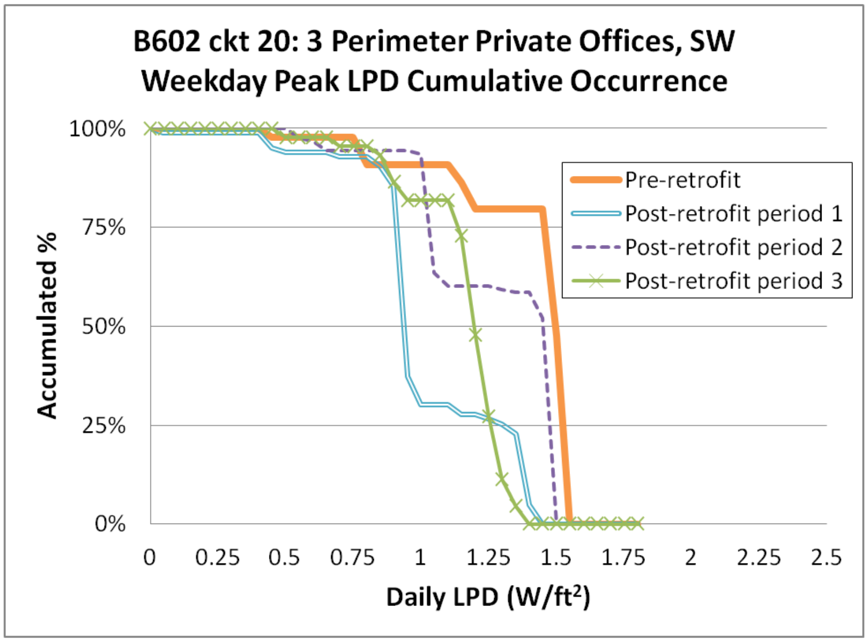



Figure 49: Building 602 Circuit 20 weekday peak lighting power density (LPD)

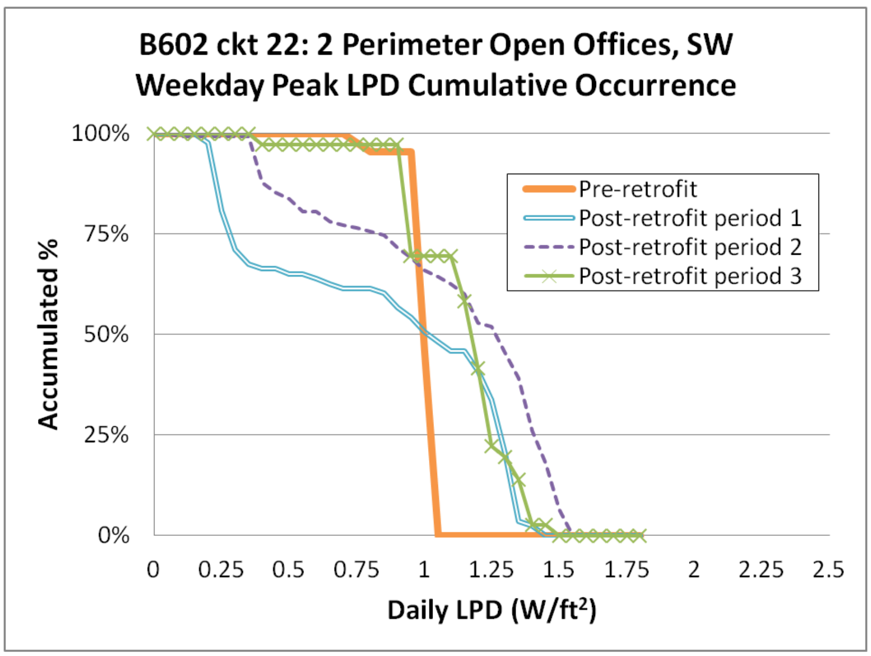



Figure 50: Building 602 Circuit 22 weekday peak lighting power density (LPD)

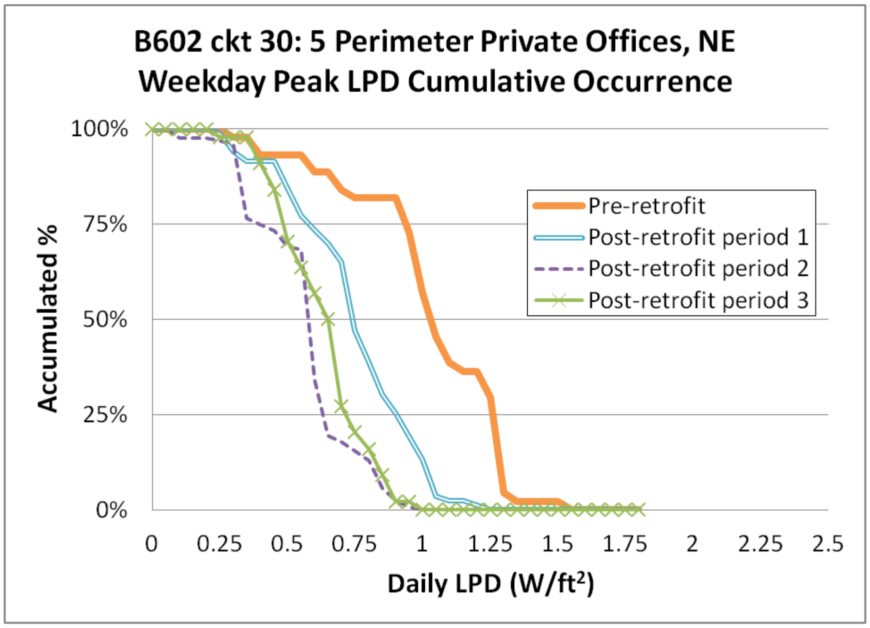



Figure 51: Building 602 Circuit 30 weekday peak lighting power density (LPD)

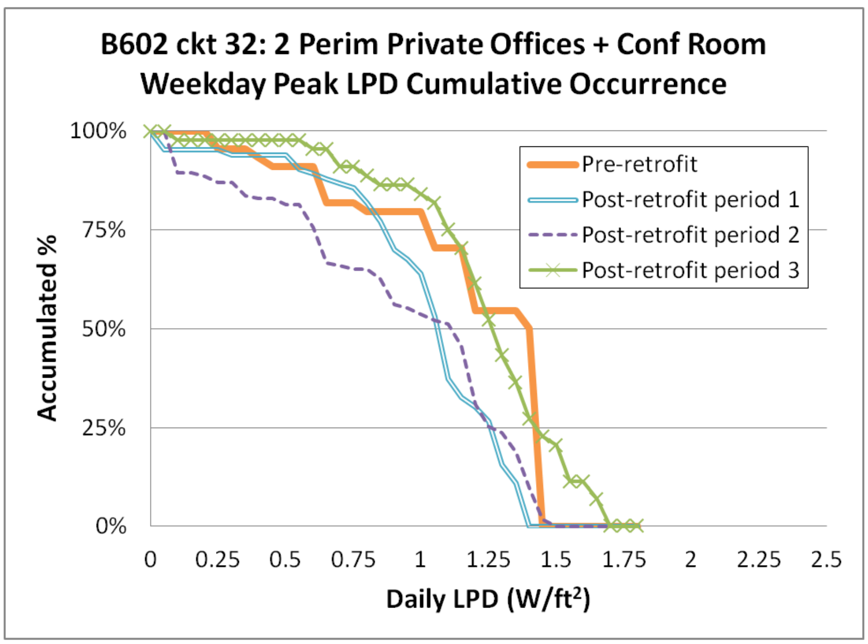



Figure 52: Building 602 Circuit 32 weekday peak lighting power density (LPD)

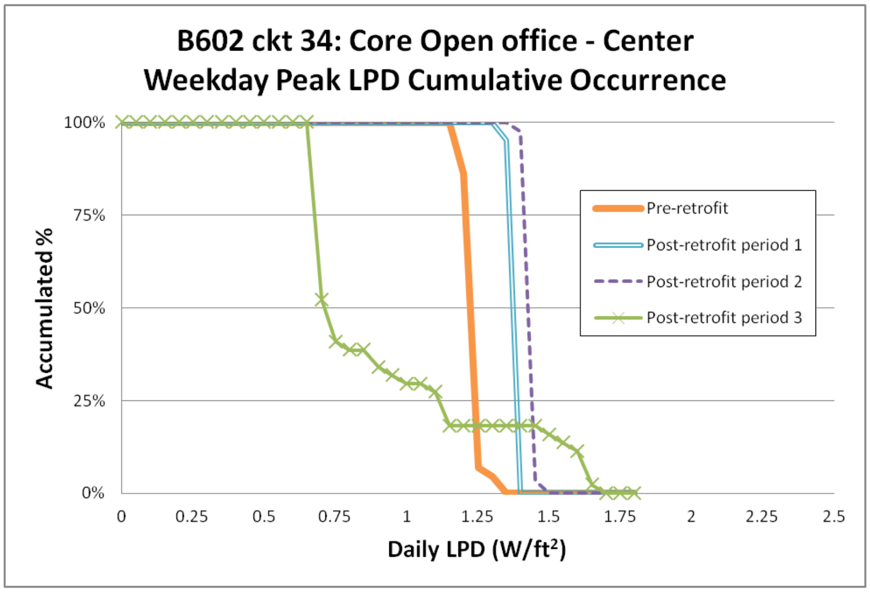



Figure 53: Building 602 Circuit 34 weekday peak lighting power density (LPD)

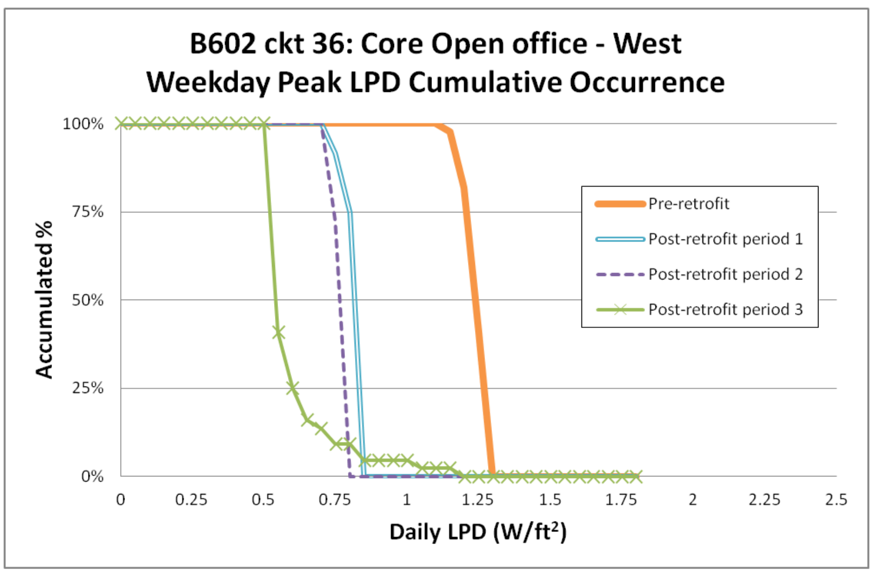



Figure 54: Building 602 Circuit 36 weekday peak lighting power density (LPD)

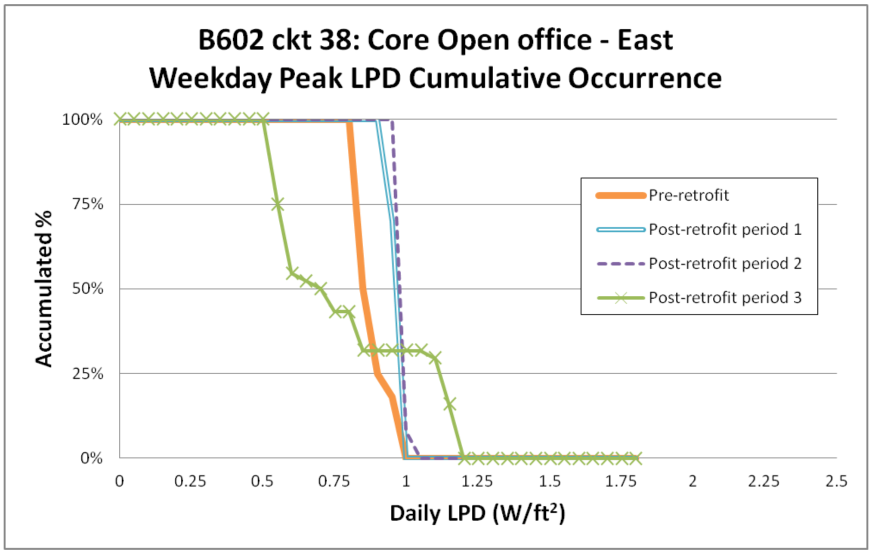



Figure 55: Building 602 Circuit 38 weekday peak lighting power density (LPD)

## 1.2. Reduce electrical energy consumption for lighting

Daily and annual energy results are presented below in Table 19. Annual EUI is calculated from average daily EUIs based on an assumed distribution of 251 weekdays, 104 weekend days, and 10 holidays per year.

The goal was to demonstrate at least a 45% reduction in EUI compared to the code baseline lighting EUI. The results demonstrated 62-64% savings over the code baseline during the post-retrofit periods, significantly exceeding the target.

Table 47: Building 602 EUI results

| | | | | Post-retrofit Periods | | |
|---|---|---|---|---|---|---|
| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline | Period 1 | Period 2 | OccuSwitch Rev |
| Weekday energy use intensity (Wh/sq ft/day) | 7.01 | 8.59 | 18.1 | 6.71 | 6.46 | 6.0 |
| Weekend energy use intensity (Wh/sq ft/day) | 0.18 | 0.25 | 0 | 0.37 | 0.40 | 1.0 |
| Holiday energy use intensity (Wh/sq ft/day) | 3.36 | 4.72 | 0 | 1.38 | 1.13 | 0.83 |
| Annual energy use intensity (kWh/sq ft/yr) | 1.81 | 2.23 | 4.54 | 1.74 | 1.68 | 1.63 |

Table 48: Building 602 post-retrofit period 1 percentage changes with respect to baselines

| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
|---|---|---|---|
| Weekday energy use intensity (Wh/sq ft/day) | 4.3% | 22.0% | 62.9% |
| Weekend energy use intensity (Wh/sq ft/day) | -105.6% | -48.0% | N/A |
| Holiday energy use intensity (Wh/sq ft/day) | 58.9% | 70.8% | N/A |
| Annual energy use intensity (kWh/sq ft/yr) | 4.2% | 22.2% | 61.8% |

Table 49: Building 602 post-retrofit period 2 percentage changes with respect to baselines

| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
|---|---|---|---|
| Weekday energy use intensity (Wh/sq ft/day) | 7.8% | 24.8% | 64.3% |
| Weekend energy use intensity (Wh/sq ft/day) | -122.2% | -60.0% | N/A |
| Holiday energy use intensity (Wh/sq ft/day) | 66.4% | 76.1% | N/A |
| Annual energy use intensity (kWh/sq ft/yr) | 7.2% | 24.7% | 63.0% |

Table 50: Building 602 post-retrofit OccuSwitch Rev (period 3) percentage changes with respect to baselines

| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
|---|---|---|---|
| Weekday energy use intensity (Wh/sq ft/day) | 14.4% | 30.2% | 66.9% |
| Weekend energy use intensity (Wh/sq ft/day) | -455.6% | -300.0% | N/A |
| Holiday energy use intensity (Wh/sq ft/day) | 75.3% | 82.4% | N/A |
| Annual energy use intensity (kWh/sq ft/yr) | 9.9% | 26.9% | 64.1% |

The figures below present cumulative occurrences of weekday daily EUIs for each circuit in Building 602. The pre-retrofit metering period included 44 weekdays while the post-retrofit metering periods 1, 2, and 3 included 83, 123, and 44 weekdays, respectively.

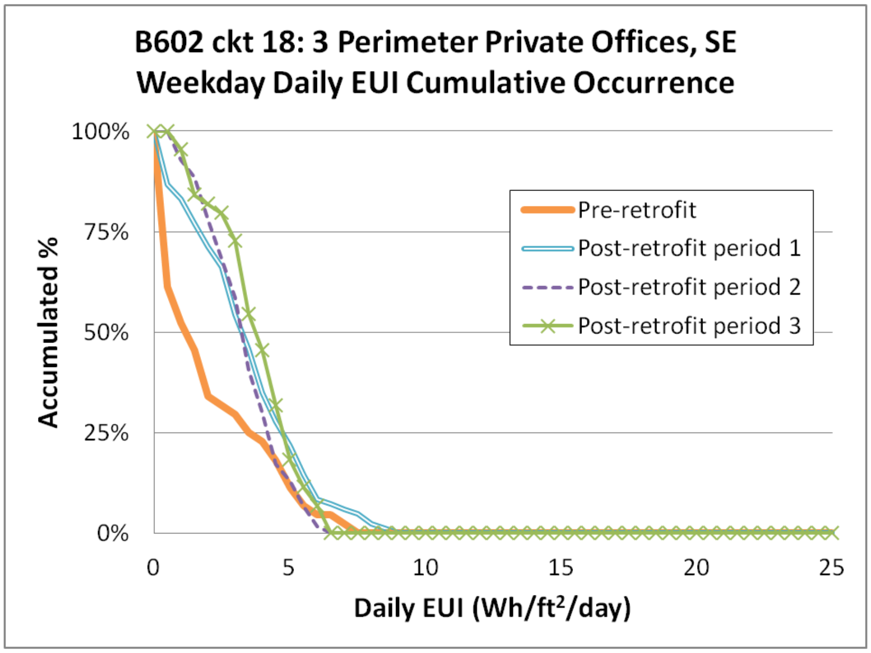



Figure 56: Building 602 Circuit 18 weekday daily energy use intensity (EUI) values

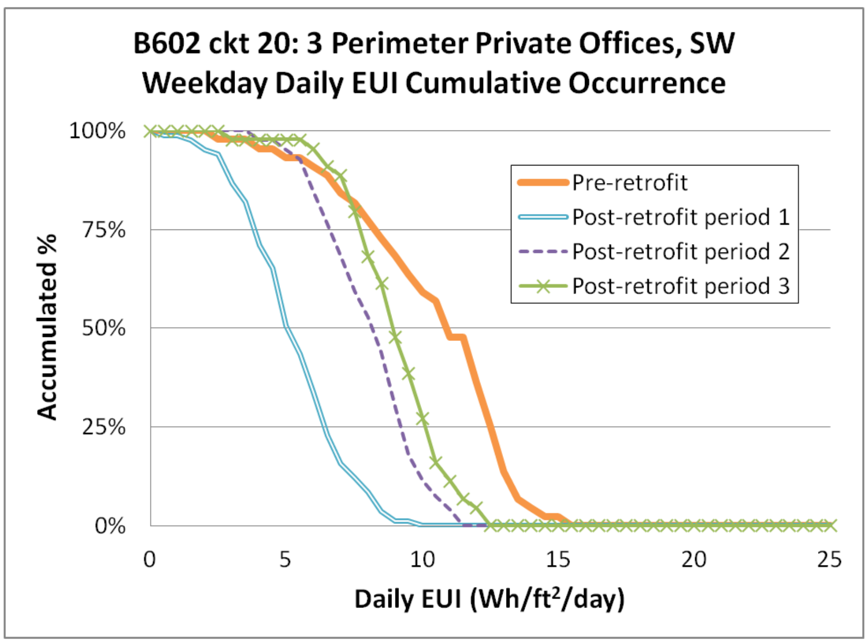



Figure 57: Building 602 Circuit 20 weekday daily energy use intensity (EUI) values

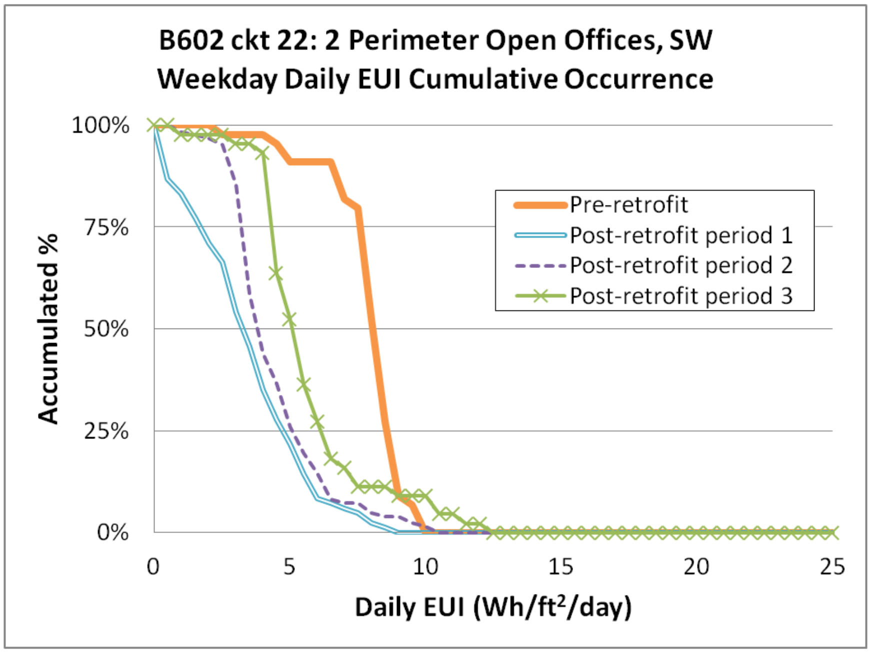



Figure 58: Building 602 Circuit 22 weekday daily energy use intensity (EUI) values

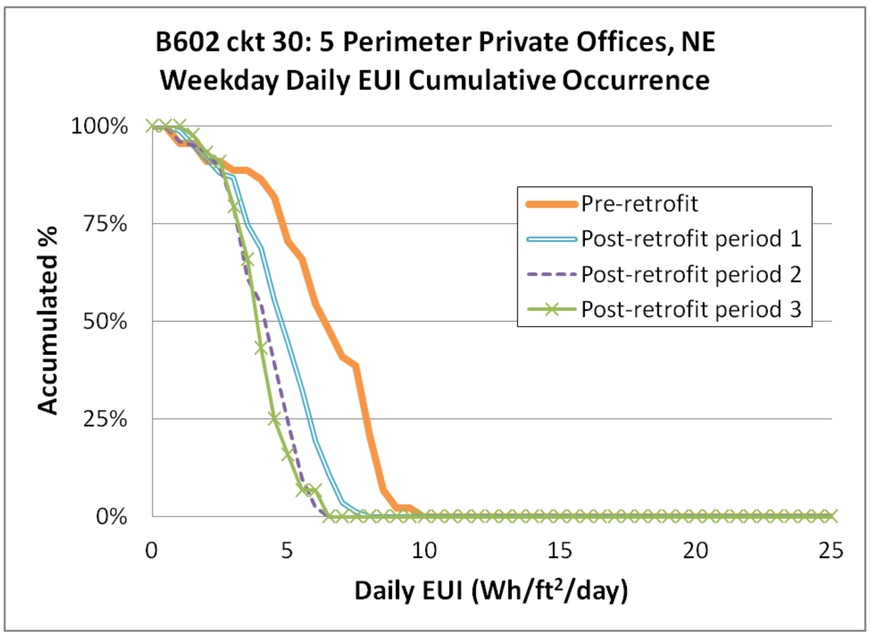



Figure 59: Building 602 Circuit 30 weekday daily energy use intensity (EUI) values

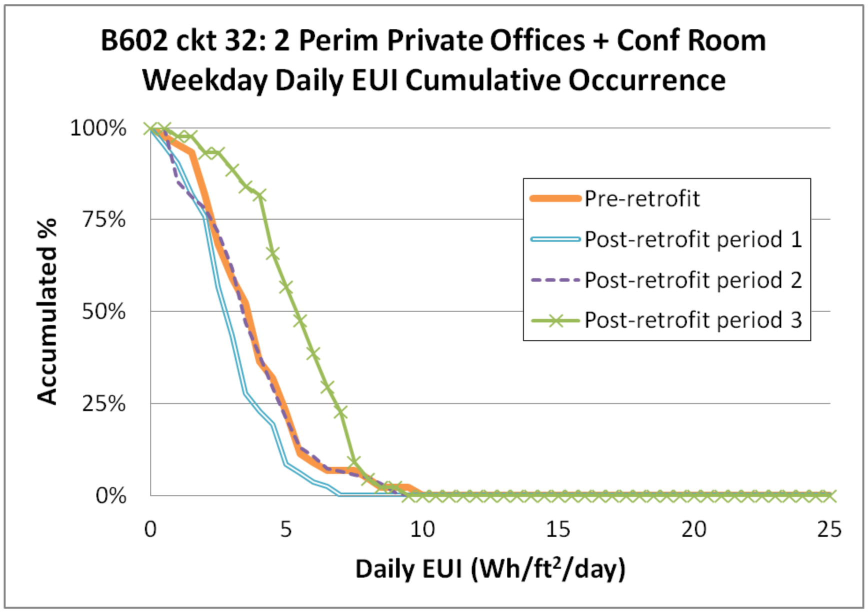



Figure 60: Building 602 Circuit 32 weekday daily energy use intensity (EUI) values

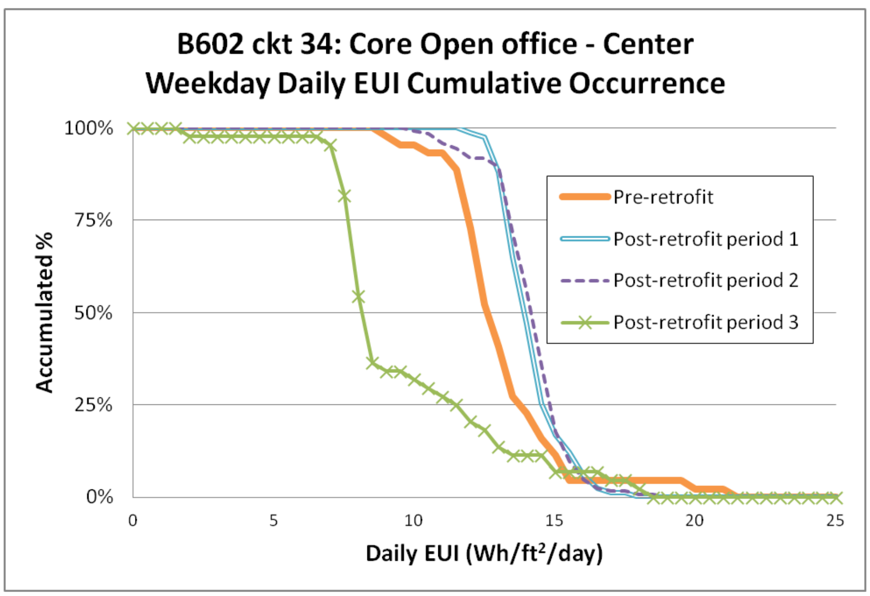



Figure 61: Building 602 Circuit 34 weekday daily energy use intensity (EUI) values

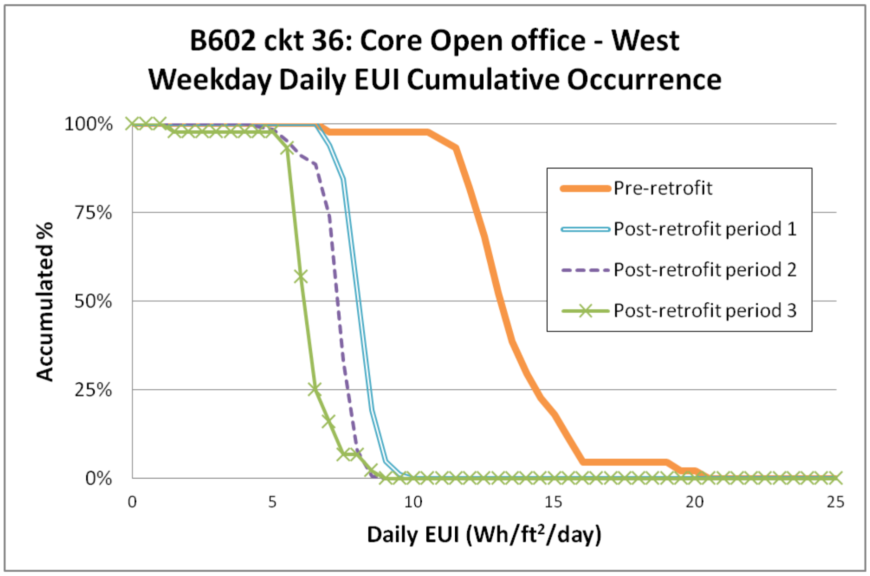



Figure 62: Building 602 Circuit 36 weekday daily energy use intensity (EUI) values

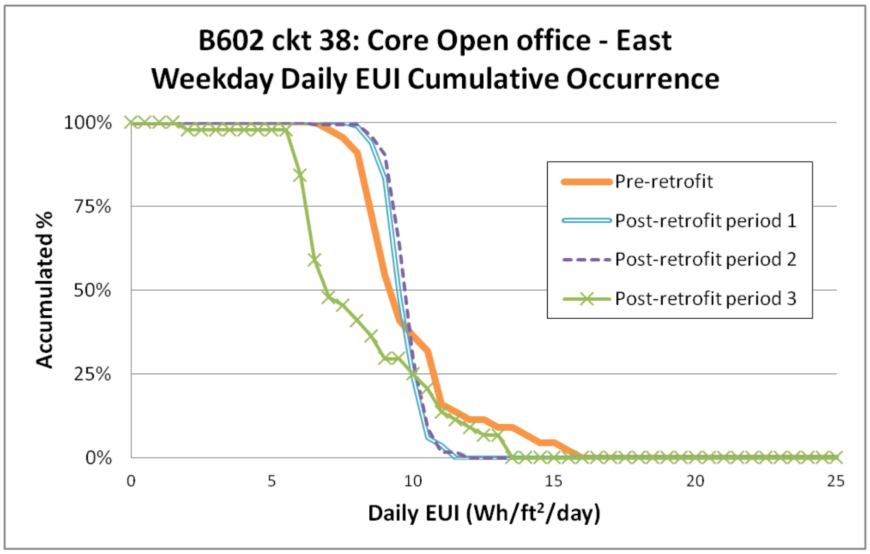



Figure 63: Building 602 Circuit 38 weekday daily energy use intensity (EUI) values

## 2. Energy Performance Of Dynalite System In Building 988 During Additional Post-retrofit Periods

To analyze the energy and demand performance of the Dynalite system installed in Building 988, a total of three discrete data sets were examined. The time intervals for the different test periods, the total number of days analyzed and the number of weekdays, weekends and holidays is given in Table 50.

Table 51. Number of days analyzed during pre-retrofit and post-retrofit periods

| | Number of Days Analyzed Over Course of Testing in Building 988 | | | | | |
|---|---|---|---|---|---|---|
| Test Period | Start | Stop | Total Days | Weekdays | Weekend Days | Holidays |
| Pre-retrofit | 8/26/2010 | 12/19/2010 | 99 | 63 | 31 | 5 |
| Post-retrofit 1 | 5/1/2011 | 12/23/2011 | 190 | 126 | 58 | 6 |
| Post-retrofit 2 | 1/1/2012 | 9/8/2012 | 243 | 169 | 70 | 4 |

The post-retrofit 1 dataset used in analysis consists of 190 days made up of 126 weekdays, 58 weekend days, and 6 holidays that were recorded from May to December 2011. The post-retrofit 2 dataset ran from Jan 2012 until September 8, 2012. This dataset consisted of 169 weekdays, 70 weekend days and 4 holidays.

## 2.1. Reduce lighting demand

The post-retrofit dataset used in energy analysis consisted of 200 days made up of 136 weekdays, 58 weekend days, and 6 holidays between May and December 2011.

Peak LPD averaged over a 15 minute interval was calculated for each week of data collected. No outliers were identified for either the pre-retrofit of post-retrofit datasets. This resulted in a peak pre-retrofit metered LPD of 0.77W/sq ft, peak adjusted pre-retrofit LPD of 1.11W/sq ft, and peak post-retrofit LPD of 0.86W/sq ft. Note that peak post-retrofit LPD is well below the installed post-retrofit level of 1.31 W/sq ft. This means that lights throughout the study area were not operating at full power simultaneously during the post-retrofit period. The reduction is likely due to a combination of tuning, daylight harvesting and lights being turned off in unoccupied spaces.

Table 52: Building 988 peak LPD results

| | | | | | Post-retrofit Period | |
|---|---|---|---|---|---|---|
| | | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline | Period 1 | Period 2 |
| | Peak LPD over a 15 minute period (W/sq ft) | 0.77 | 1.11 | 1.81 | 0.86 | 0.82 |
| % savings compared to | Pre-retrofit metered | - | - | - | -12% | -7% |
| | Adjusted pre-retrofit | - | - | - | 23% | 26% |
| | Code baseline | - | - | - | 52% | 55% |

The goal was to achieve at least a 25% reduction in peak LPD compared to the code baseline. The results show a 52-55% reduction compared to the code baseline, substantially exceeding the target for the two post-retrofit periods.

The figures below present cumulative occurrences of weekday daily peak LPDs for each circuit in Building 988. The pre-retrofit metering period included 63 weekdays while the post-retrofit metering periods 1 and 2 included 136 and 169 weekdays, respectively.

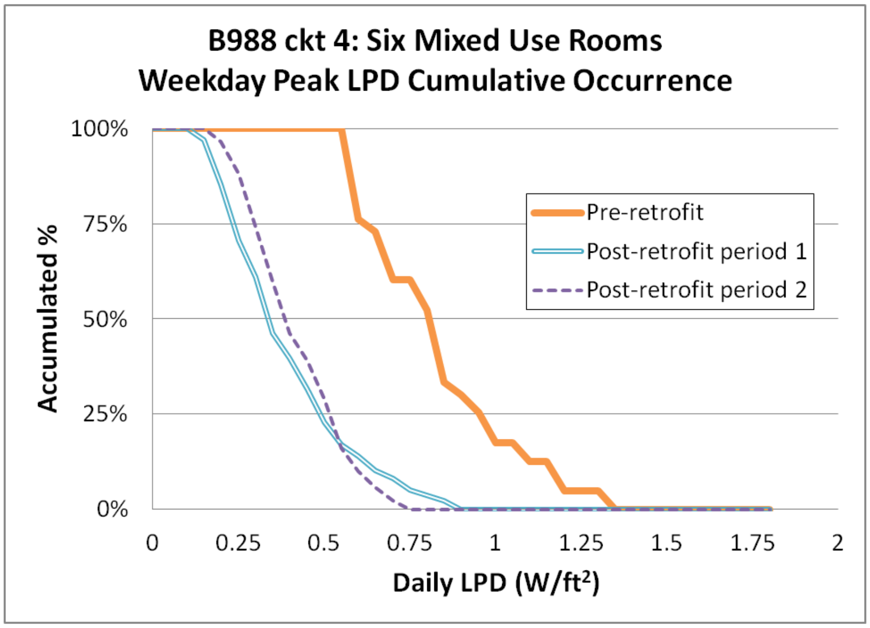



Figure 64: Building 988 circuit 4 weekday daily peak lighting power density (LPD) values

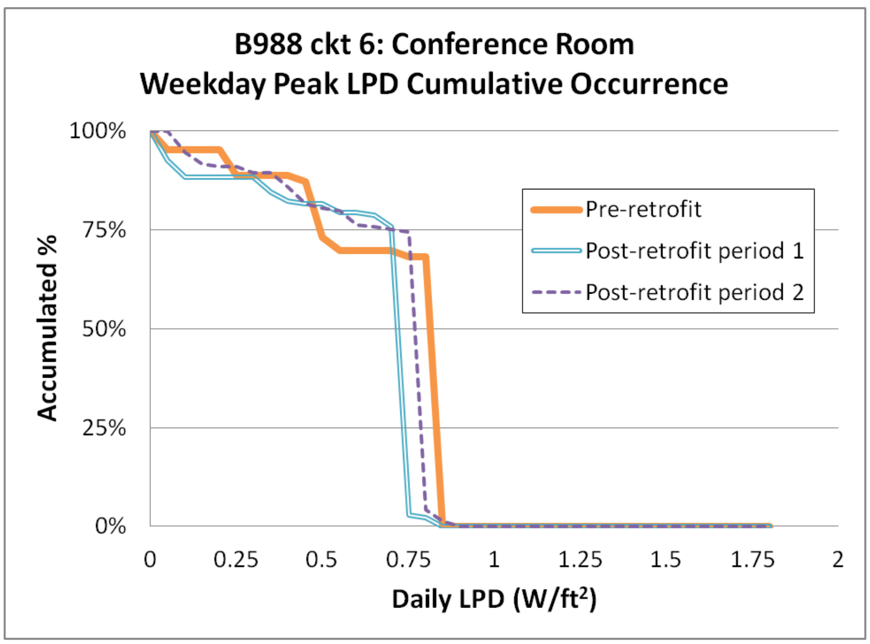



Figure 65: Building 988 circuit 6 weekday daily peak lighting power density (LPD) values

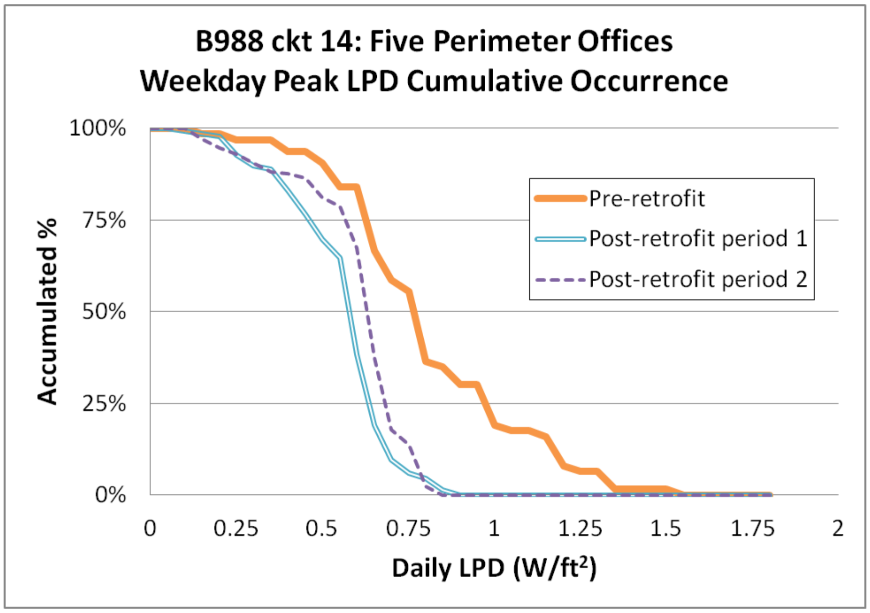



Figure 66: Building 988 circuit 14 weekday daily peak lighting power density (LPD) values

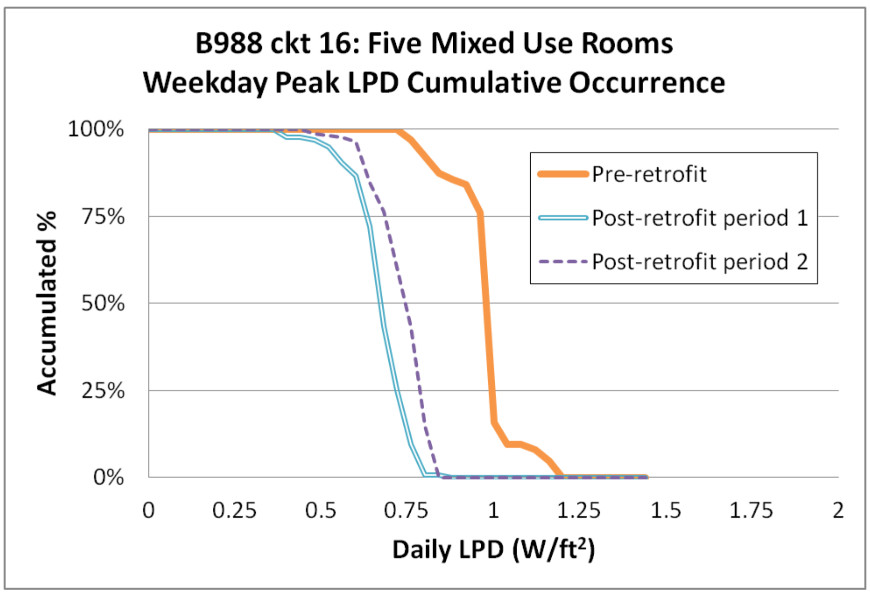



Figure 67: Building 988 circuit 16 weekday daily peak lighting power density (LPD) values

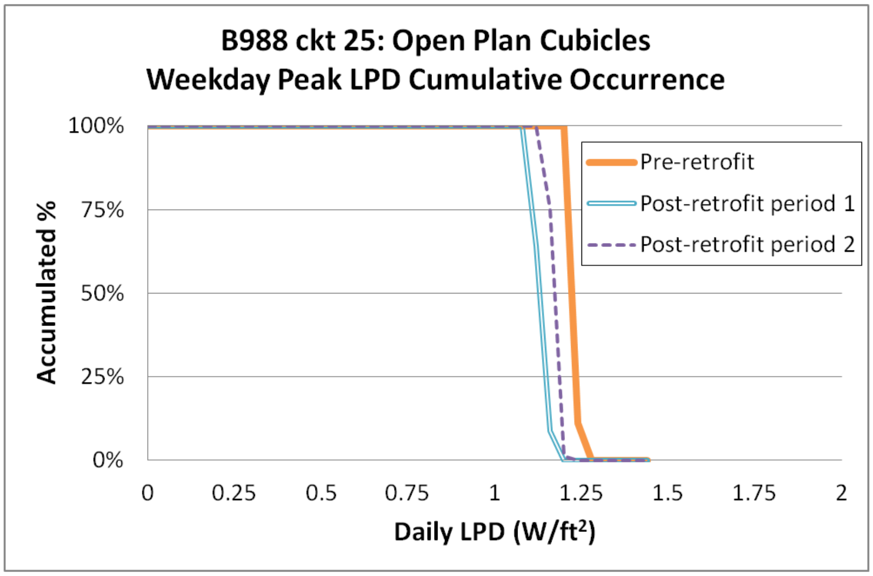



Figure 68: Building 988 circuit 25 weekday daily peak lighting power density (LPD) values

## 2.2. Reduce electrical energy use for lighting

Daily and annual energy results are presented below in Table 53. Annual EUI is calculated from average daily EUIs based on an assumed 251 weekdays, 104 weekend days, and 10 holidays per year. For the pre-retrofit data, which exhibited statistically significant variation associated with day of the week, weekday EUI was calculated as an average of the EUI associated with each day of the week.

The goal was to demonstrate at least a 45% reduction in annual EUI compared to the code baseline. The results show a 43% reduction during post-retrofit period 1 and a 46% reduction during post-retrofit period 2. Post-retrofit period 1 comes close to the goal but fails to meet it but post-retrofit period 2 exceeds goal slightly. This demonstrates that this goal is achievable at this site but continued fine-tuning of system and diligent maintenance would be necessary.

Table 53: Building 988 EUI results

| | | | | Post-retrofit Periods | |
|---|---|---|---|---|---|
| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline | Period 1 | Period 2 |
| Weekday energy use intensity (Wh/sq ft/day) | 8.02 | 12.14 | 18.1 | 8.68 | 8.28 |
| Weekend energy use intensity (Wh/sq ft/day) | 3.77 | 5.76 | 0 | 3.58 | 3.11 |
| Holiday energy use intensity (Wh/sq ft/day) | 5.06 | 7.73 | 0 | 4.64 | 4.35 |
| Annual energy use intensity (kWh/sq ft/yr) | 2.46 | 3.73 | 4.54 | 2.60 | 2.45 |

Table 54: Building 988 post-retrofit period 1 percentage changes with respect to baselines

| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
|---|---|---|---|
| Weekday energy use intensity (Wh/sq ft/day) | -8.2% | 28.5% | 52.0% |
| Weekend energy use intensity (Wh/sq ft/day) | 5.0% | 37.8% | N/A |
| Holiday energy use intensity (Wh/sq ft/day) | 8.3% | 40.0% | N/A |
| Annual energy use intensity (kWh/sq ft/yr) | -5.7% | 30.3% | 42.8% |

Table 55: Building 988 post-retrofit period 2 percentage changes with respect to baselines

| | Pre-retrofit metered | Adjusted pre-retrofit | Code baseline |
|---|---|---|---|
| Weekday energy use intensity (Wh/sq ft/day) | -3.2% | 31.8% | 54.3% |
| Weekend energy use intensity (Wh/sq ft/day) | 17.4% | 46.0% | N/A |
| Holiday energy use intensity (Wh/sq ft/day) | 14.0% | 43.7% | N/A |
| Annual energy use intensity (kWh/sq ft/yr) | 0.6% | 34.5% | 46.2% |

The figures below present cumulative occurrences of weekday daily EUIs for each circuit in Building 988. The pre-retrofit metering period included 63 weekdays while the post-retrofit metering periods 1 and 2 included 136 and 169 weekdays, respectively.

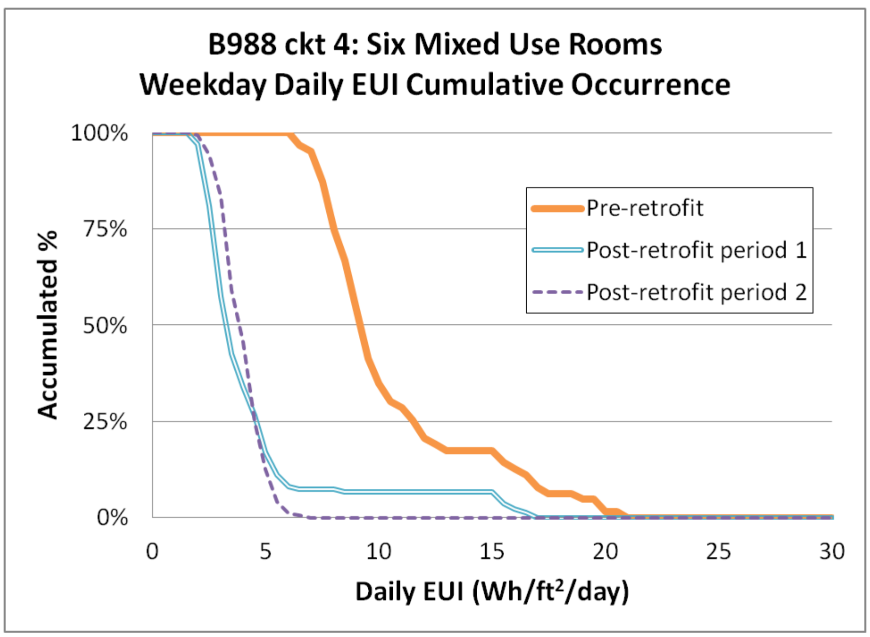



Figure 69: Building 988 circuit 4 weekday daily energy use intensity (EUI) values

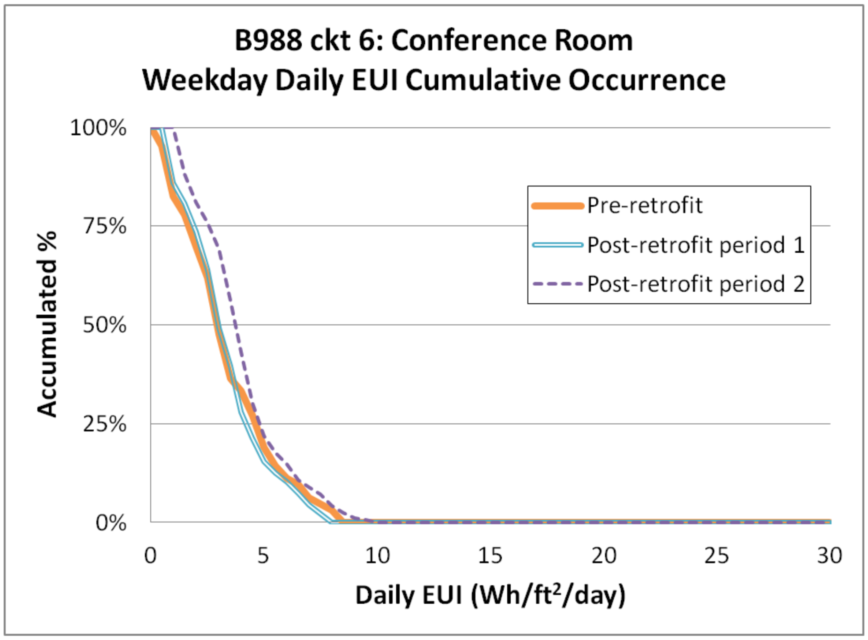



Figure 70: Building 988 circuit 6 weekday daily energy use intensity (EUI) values

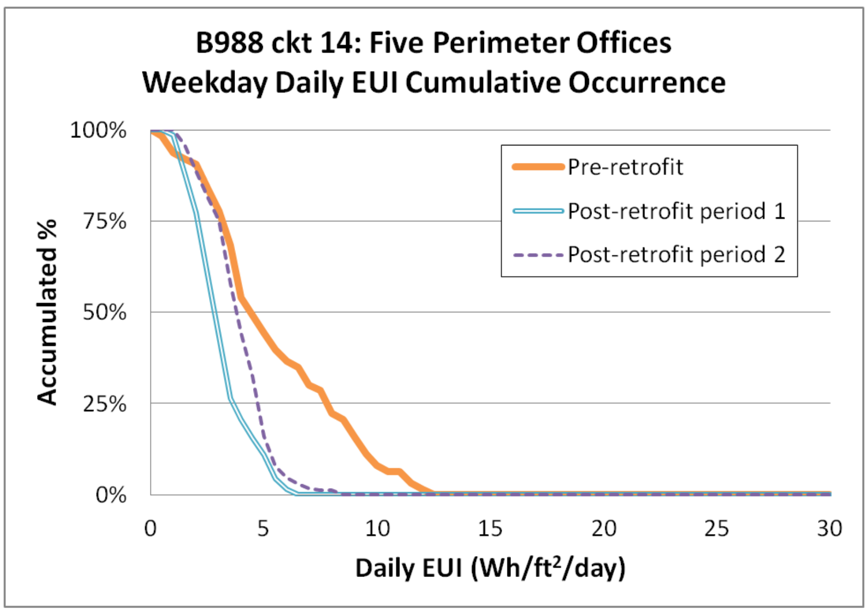



Figure 71: Building 988 circuit 14 weekday daily energy use intensity (EUI) values

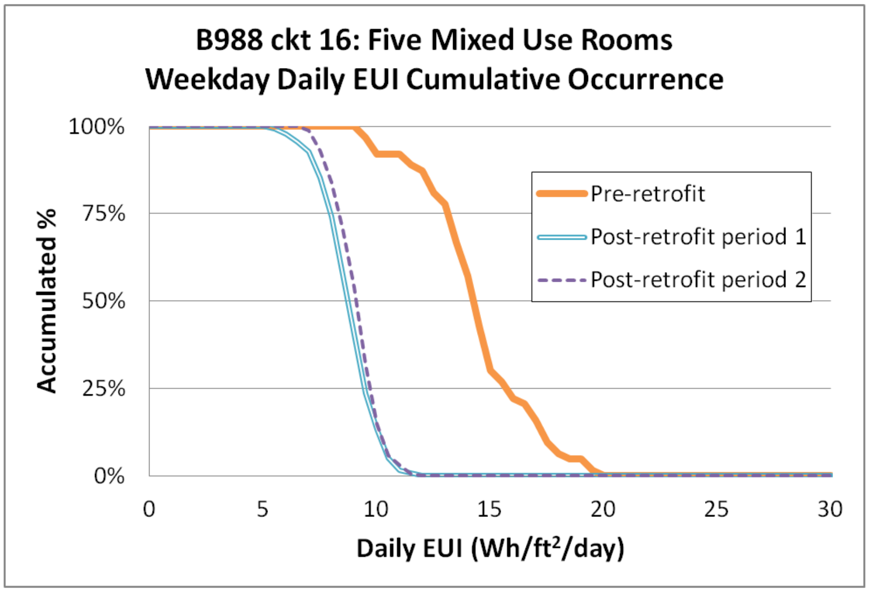



Figure 72: Building 988 circuit 16 weekday daily energy use intensity (EUI) values

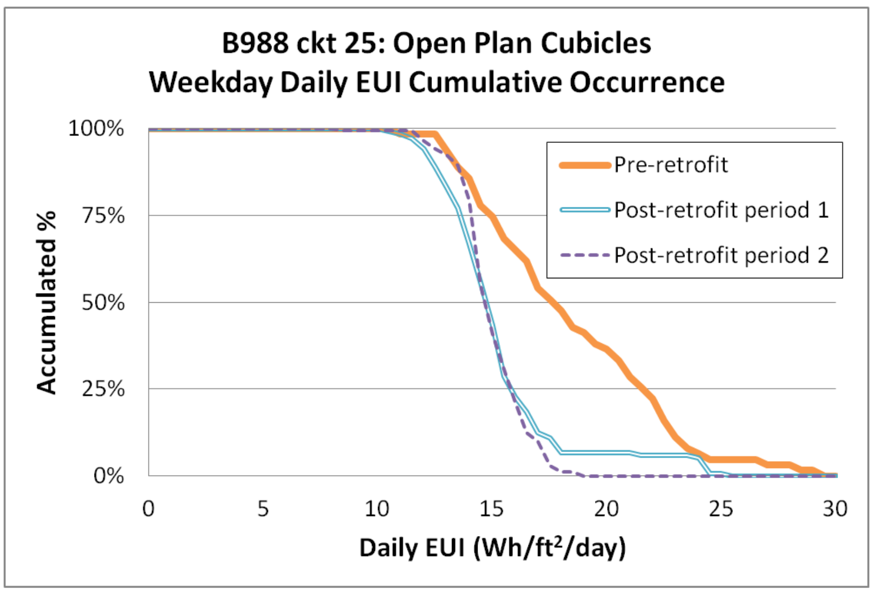



Figure 73: Building 988 circuit 25 weekday daily energy use intensity (EUI) values

## Appendix F: Installer Interview

The script for the installer phone interviews is provided below. This script was loosely followed during each phone interview, with some variation. Surveys were performed by LBNL.

Installer: ___________________________________________
Building: ___________________________________________
Date and time surveyed: ______________________________
Surveyed by: ________________________________________
Introduction: One survey per building (so we'll repeat this 3 times), candid feedback is the goal, please don't hold back negative comments if you have them, the more comments you're able to give the better, etc.

1. Please state if your work in building ______________ included the following:
   - ☐ Fixture replacement
   - ☐ Fixture renovation
   - ☐ Ballast replacement
   - ☐ Wall switch replacement
   - ☐ Sensor installation
   - ☐ Sensor placement
   - ☐ Control wire installation
2. Please describe any additional work that you performed in building ________, and/or elaborate on the above tasks:
3. Please rate the difficulty of performing the following tasks on a scale from 1 to 5 (1=very straightforward and 5=very challenging) (ask only about performed tasks):
   a. Fixture replacement/renovation:
   b. Ballast replacement:
   c. Wall switch replacement:
   d. Sensor placement/installation:
   e. Control wire installation:
   f. ____________________________:
   g. ____________________________:
4. Please comment on what influenced the difficulty of these tasks:
5. Please rate your response to the following questions (1=strongly disagree, 2=disagree, 3=neutral, 4=agree, 5 =strongly agree):
   a. The project was similar to other lighting retrofit projects I have worked on:
   b. The project presented installation challenges that I was not familiar with:
   c. This installation took longer and required more effort than typical installations of a similar size:
   d. The written installation instructions were clear and comprehensive:
   e. During the process, my questions were answered clearly and promptly:

    f. I have concerns about problems that could have occurred during the installation due to confusing installation processes, unusual installation tasks, inadequate instructions, etc:
        i. (If 4 or 5:) Please describe your concerns:
    g. I could have performed this installation with minimal support beyond the provided written materials:
    h. I could perform future installations of the same lighting and control system with minimal support beyond the provided written materials:
6. Do you have any comments on the overall scope of work (what made it challenging, what was easier/harder than expected, etc)?
7. Do you have additional feedback about the installation process, instructions, improvements that could be incorporated into future projects, etc:

Thank you!

## Appendix G: Occupant Survey

The pre-retrofit installer survey is presented below. The fixture images on page two were modified in the actual surveys to represent the fixtures installed in the study areas.

### Privacy Statement

**Privacy Statement**

This survey is being conducted to determine occupant preferences about office lighting. The information gathered may be used by employers or facility managers to make informed choices about lighting, and to improve the state of knowledge about lighting and worker satisfaction.

**About this Survey**

- **Responses are anonymous** — Your responses to this on-line survey will be sent directly to the survey administration company server which is not associated with and cannot be accessed by your employer. This ensures that your specific responses will never be available to the organization or individuals that you work for. Your responses will only be available as aggregated group information.
- **Participation is Voluntary** — This survey is entirely voluntary, and you are free to choose at any time whether or not to provide responses to the survey or individual questions.
- **Your Rights** — If you have questions about your rights as a participant of this research survey or this website, please email the Institutional Review Board at Pacific Northwest National Laboratory. A research specialist will respond to your question promptly.

**Accept**

## Lighting Satisfaction Survey

Page 1 of 9

**What is your age?**

- ◯ 30 or under
- ◯ 31 - 40
- ◯ 41 - 50
- ◯ Over 50

**What is your gender?**

- ◯ Female
- ◯ Male

Back / **Next**

# Lighting Satisfaction Survey



On a typical day, how long are you in your personal workspace?

- More than 6 hours
- 4-6 hours
- 2-4 hours
- Less than 2 hours

Are you able to see out a window while sitting in your workspace?

- Yes
- No

Do you sit next to a window?

- Yes
- No

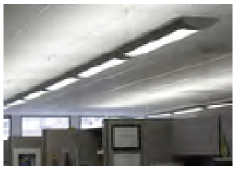
Which of the following best describes your personal workspace?

- Cubicles in open area
- Enclosed private office

Overall, is the lighting comfortable?

- Yes
- No

Which of the following types of lighting fixtures most closely resembles the general lighting in your immediate workspace?



- Other (picture not shown)

Description of Overhead Lighting, if "Other."

Back / **Next**

## Lighting Satisfaction Survey

Page 3 of 9

To what extent do you agree or disagree with the following statements about the lighting in your personal workspace? Please check "N/A" or "Not Applicable," if a given question does not apply to you.

| | Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree | Does Not Apply |
|---|---|---|---|---|---|---|
| My work surface is evenly lighted without very bright or dim spots. | ○ | ○ | ○ | ○ | ○ | ○ |
| The lighting fixtures in the general office area around my workspace are nice-looking. | ○ | ○ | ○ | ○ | ○ | ○ |
| The light fixtures are too bright. | ○ | ○ | ○ | ○ | ○ | ○ |
| The lighting control system allows me to create the lighting conditions I want. | ○ | ○ | ○ | ○ | ○ | ○ |
| The lighting feels gloomy. | ○ | ○ | ○ | ○ | ○ | ○ |
| The lights flicker throughout the day. | ○ | ○ | ○ | ○ | ○ | ○ |
| The lighting helps create a good image for the organization. | ○ | ○ | ○ | ○ | ○ | ○ |
| My skin is an unnatural tone under the lighting. | ○ | ○ | ○ | ○ | ○ | ○ |
| The room surfaces (walls, ceilings) have a pleasant brightness. | ○ | ○ | ○ | ○ | ○ | ○ |

Back / **Next**

## Lighting Satisfaction Survey



How would you rate the lighting in your workspace for each of the following tasks? Please check "NA," or "not applicable," if a given question does not apply to you.

| | Much Too Bright | Too Bright | Just Right | Too Dim | Much Too Dim | Does Not Apply |
|---|---|---|---|---|---|---|
| Reading from paper | ○ | ○ | ○ | ○ | ○ | ○ |
| Reading from a computer screen | ○ | ○ | ○ | ○ | ○ | ○ |
| Writing on paper | ○ | ○ | ○ | ○ | ○ | ○ |
| Typing on keyboard | ○ | ○ | ○ | ○ | ○ | ○ |
| Using the telephone | ○ | ○ | ○ | ○ | ○ | ○ |
| Filing or locating papers | ○ | ○ | ○ | ○ | ○ | ○ |
| Face to face conversations | ○ | ○ | ○ | ○ | ○ | ○ |

Back / **Next**

## Lighting Satisfaction Survey

Page 5 of 9

How often do you experience any of the following conditions when in your personal workspace during an average day?

For the purpose of answering these questions, consider the definition of glare to be unwanted light. E.g., noise is to sound, as glare is to light.

| | Never | Rarely | Sometimes | Often | Always |
|---|---|---|---|---|---|
| Glare reflected from your work surface | | | | | |
| Glare from the light fixtures reflected on your computer screen | | | | | |
| Glare from the window reflected on your computer screen | | | | | |
| Overhead glare from the general lighting | | | | | |
| Glare from your task lighting | | | | | |
| Direct glare from a window | | | | | |
| Direct glare from the light fixtures | | | | | |

Back / **Next**

## Lighting Satisfaction Survey

Page 6 of 9

Lighting comes in a range of colors, from a "warm" white to "cool" white. "Warm" light is often described as slightly yellow in appearance, and "cool" light is often described as slightly blue in appearance. Using the indicated color range, please indicate:

| | Very Warm | Somewhat Warm | Neutral | Somewhat Cool | Very Cool | Don't Know |
|---|---|---|---|---|---|---|
| What is the color appearance of the lighting in your personal workspace? | ○ | ○ | ○ | ○ | ○ | ○ |
| What would you prefer for the color appearance of the lighting in your personal workspace? | ○ | ○ | ○ | ○ | ○ | ○ |

Back / **Next**

## Lighting Satisfaction Survey

Page 7 of 9

How often do you experience any of the following conditions when in your personal workspace?

| | Never | Rarely | About Once per Month | About Once per Week | Every Day |
|---|---|---|---|---|---|
| "Burning" or tired eyes after reading extensively | ○ | ○ | ○ | ○ | ○ |
| "Burning" or tired eyes after using computer extensively | ○ | ○ | ○ | ○ | ○ |
| I have to take a break to let my eyes recover | ○ | ○ | ○ | ○ | ○ |
| Headache that you think is caused by your lighting | ○ | ○ | ○ | ○ | ○ |

Back / **Next**

## Lighting Satisfaction Survey

Page 8 of 9

If you could change the lighting in your office, what would you do? Please check all that apply.

- ☐ Change the location of the general lighting fixtures relative to your workstation
- ☐ Make the general lighting fixtures produce more light
- ☐ Make the general lighting fixtures less glary
- ☐ Change the aesthetic appearance of the lighting fixtures
- ☐ Change the color appearance of the light produced by the lighting fixtures
- ☐ Add a task light
- ☐ Be able to control the brightness/light output of the general lighting fixtures with a dimmer or high/low switch
- ☐ Get better access to a window view
- ☐ Get better access to daylight
- ☐ Have light bulbs replaced faster when they burn out and fixtures repaired faster when they break
- ☐ I would not change anything

Back / **Next**

## Lighting Satisfaction Survey

Page 9 of 9

Please feel free to submit any other comments about your lighting below:

Please feel free to submit any other comments about this survey below:

Back / **Submit**

# Appendix H: Occupant Survey Results

Occupant survey results are summarized below for each building.
Building 279:

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Which of the following best describes the type of work you do? | People management, leadership, and/or training | 1 | 100% | 1 | 50% |
| | Computer aided design, engineering, or software development | 0 | 0% | 0 | 0% |
| | Combination of computer work, paper tasks, phone calls and meetings | 0 | 0% | 1 | 50% |
| | Facility Management | 0 | 0% | 0 | 0% |
| | Other | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| What is your age? | 30 or under | 1 | 100% | 1 | 50% |
| | 31-40 | 0 | 0% | 0 | 0% |
| | 41-50 | 0 | 0% | 1 | 50% |
| | over 50 | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| What is your gender? | female | 0 | 0% | 1 | 50% |
| | Male | 1 | 100% | 1 | 50% |
| | Total | 1 | 100% | 2 | 100% |
| Which of the following best describes your personal workspace? | Enclosed private office | 1 | 100% | 2 | 100% |
| | Cubicles with Partitions above standing eye level | 0 | 0% | 0 | 0% |
| | Cubicles with partitions below standing eye level | 0 | 0% | 0 | 0% |
| | Other | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| What type of computer screen do you have? | Laptop | 0 | 0% | 0 | 0% |
| | Flat Panel Screen | 0 | 0% | 2 | 100% |
| | Traditional Screen | 1 | 100% | 0 | 0% |
| | Other | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| On a typical day, how long | More than 6 hours | 0 | 0% | 1 | 50% |
| | 4-6 hours | 1 | 100% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| are you in your personal workspace? | 2-4 hours | 0 | 0% | 0 | 0% |
| | Less than 2 hours | 0 | 0% | 1 | 50% |
| | Total | 1 | 100% | 2 | 100% |
| Are you able to see out a window while sitting in your workspace? | Yes | 1 | 100% | 2 | 100% |
| | No | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| If "Yes," do you like the view? | Yes | 1 | 100% | 2 | 100% |
| | No | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Do you sit adjacent to a window? | Yes | 0 | 0% | 1 | 50% |
| | No | 1 | 100% | 1 | 50% |
| | Total | 1 | 100% | 2 | 100% |
| Which of the following most closely resembles the overhead lighting in your immediate work space (check all that apply)? | Picture 1 | 0 | 0% | 0 | 0% |
| | Picture 2 | 0 | 0% | 1 | 50% |
| | Picture 3 | 0 | 0% | 1 | 50% |
| | Other | 0 | 0% | 0 | 0% |
| | Total | 0 | 0% | 2 | 100% |
| Overall, is the lighting comfortable? | Yes | 1 | 100% | 2 | 100% |
| | No | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Which of the following types of lighting fixtures most closely resembles the task lighting in your personal workspace? | Undercabinet Task light | 0 | 0% | 0 | 0% |
| | Destop Task light | 0 | 0% | 0 | 0% |
| | I do not have a task light | 1 | 100% | 2 | 100% |
| | Total | 1 | 100% | 2 | 100% |
| Which of the following most closely | Uniformly bright walls | 0 | 0% | 2 | 100% |
| | Uneven light distribution on walls | 0 | 0% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| resembles the lighting on the walls in your general office area? (check all that apply) | Accent Lighting on artwork only | 0 | 0% | 0 | 0% |
| | Walls are dim | 0 | 0% | 0 | 0% |
| | Other | 0 | 0% | 0 | 0% |
| | Do not know | 1 | 100% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Do the overhead lighting fixtures in your workspace turn on automatically (when you enter the space, on a set schedule, or both)? | Yes | 0 | 0% | 1 | 50% |
| | No | 1 | 100% | 1 | 50% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Do the overhead lighting fixtures in your workspace turn off automatically (when you leave the space, on a set schedule, or both)? | Yes | 0 | 0% | 1 | 50% |
| | No | 1 | 100% | 1 | 50% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| If your lights turn off automatically, can you turn them back on from your immediate work area? | Yes | 0 | 0% | 1 | 100% |
| | No | 0 | 0% | 0 | 0% |
| | Do not know/ Does not apply | 1 | 100% | 0 | 0% |
| | Total | 1 | 100% | 1 | 100% |
| Can you control the overhead lights in your personal | Yes | 1 | 100% | 2 | 100% |
| | No | 0 | 0% | 0 | 0% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| workspace without changing the lights in neighboring areas? | Total | 1 | 100% | 2 | 100% |
| How are your overhead lights controlled (check all that apply)? | Switch at wall | 1 | 100% | 2 | 100% |
| | Handheld remote | 0 | 0% | 0 | 0% |
| | Interface at your computer | 0 | 0% | 0 | 0% |
| | Automated system/controlled by building management | 0 | 0% | 0 | 0% |
| | Other (Please specify) | 0 | 0% | 0 | 0% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| To what extent can light levels from your overhead lights be adjusted? | Lights turn on and off only | 1 | 100% | 1 | 50% |
| | Light level settings are available for high, low, and/or medium | 0 | 0% | 0 | 0% |
| | Continuous dimming available | 0 | 0% | 1 | 50% |
| | Total | 1 | 100% | 2 | 100% |
| What type of control do you have for your task lighting? | On/Off switch | 1 | 100% | 0 | 0% |
| | Dimmer switch | 0 | 0% | 0 | 0% |
| | Other (please specify | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 2 | 100% |
| | Total | 1 | 100% | 2 | 100% |
| What type of shading system do you have to control the amount of daylight entering your windows? | Manual blinds (e.g., Venetian blinds) | 1 | 100% | 1 | 50% |
| | Manual windo shades(e.g.,roller shades) | 0 | 0% | 0 | 0% |
| | Automatic blinds or shades | 0 | 0% | 1 | 50% |
| | Other (please specify) | 0 | 0% | 0 | 0% |
| | No shading control | 0 | 0% | 0 | 0% |
| | I have no daylight in my workspace | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Can you control the amount of daylight entering your windows without affecting other occupants? | Yes | 1 | 100% | 2 | 100% |
| | No | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| I am satisfied with my ability to control my overhead lighting. | Strongly Disagree | 0 | 0% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 1 | 100% | 1 | 50% |
| | Strongly Agree | 0 | 0% | 1 | 50% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| I am satisfied with my ability to control my task lighting. | Strongly Disagree | 0 | 0% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 1 | 100% | 1 | 50% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 1 | 50% |
| | Total | 1 | 100% | 2 | 100% |
| I am satisfied with my ability to control my window shades or blinds. | Strongly disagree | 0 | 0% | 1 | 50% |
| | Disagree | 1 | 100% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 0 | 0% | 0 | 0% |
| | Strongly Agree | 0 | 0% | 1 | 50% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| My work surface is evenly lighted without very bright or dim spots. | Strongly Disagree | 0 | 0% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 1 | 100% | 0 | 0% |
| | Strongly Agree | 0 | 0% | 1 | 100% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 1 | 100% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| The lights flicker throughout the day. | Strongly Disagree | 1 | 100% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 1 | 100% |
| | Agree | 0 | 0% | 0 | 0% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 1 | 100% |
| My skin is an unnatural tone under the lighting. | Strongly Disagree | 0 | 0% | 1 | 100% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 1 | 100% | 0 | 0% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 1 | 100% |
| The lighting fixtures in the general office area around my workspace are nice-looking. | Strongly Disagree | 0 | 0% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 1 | 100% | 1 | 50% |
| | Agree | 0 | 0% | 0 | 0% |
| | Strongly Agree | 0 | 0% | 1 | 50% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| The lighting helps create a good image for the organization. | Strongly Disagree | 0 | 0% | 0 | 0% |
| | Disagree | 1 | 100% | 0 | 0% |
| | Neutral | 0 | 0% | 1 | 50% |
| | Agree | 0 | 0% | 1 | 50% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| The room surfaces (walls, ceilings) have a pleasant brightness. | Strongly Disagree | 0 | 0% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 1 | 100% | 0 | 0% |
| | Agree | 0 | 0% | 2 | 100% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Paper Tasks (reading and writing) | Much too Bright | 0 | 0% | 0 | 0% |
| | Too Bright | 0 | 0% | 0 | 0% |
| | Just Right | 1 | 100% | 2 | 100% |
| | Too Dim | 0 | 0% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Reading from a computer screen | Much too Bright | 0 | 0% | 0 | 0% |
| | Too Bright | 1 | 100% | 0 | 0% |
| | Just Right | 0 | 0% | 2 | 100% |
| | Too Dim | 0 | 0% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Typing on keyboard | Much too Bright | 0 | 0% | 1 | 50% |
| | Too Bright | 0 | 0% | 0 | 0% |
| | Just Right | 1 | 100% | 1 | 50% |
| | Too Dim | 0 | 0% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Filing or locating papers | Much too Bright | 0 | 0% | 0 | 0% |
| | Too Bright | 0 | 0% | 0 | 0% |
| | Just Right | 0 | 0% | 2 | 100% |
| | Too Dim | 1 | 100% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Face to face conversations | Much too Bright | 0 | 0% | 0 | 0% |
| | Too Bright | 0 | 0% | 0 | 0% |
| | Just Right | 1 | 100% | 2 | 100% |
| | Too Dim | 0 | 0% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Glare reflected from your work surface | Never | 0 | 0% | 1 | 50% |
| | Rarely | 0 | 0% | 0 | 0% |
| | Sometimes | 1 | 100% | 1 | 50% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Glare from the light fixtures | Never | 0 | 0% | 1 | 50% |
| | Rarely | 0 | 0% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| reflected on your computer screen | Sometimes | 1 | 100% | 1 | 50% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Glare from the window reflected on your computer screen | Never | 0 | 0% | 1 | 50% |
| | Rarely | 0 | 0% | 0 | 0% |
| | Sometimes | 1 | 100% | 1 | 50% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Glare from the overhead lighting in your immediate workspace (usually experienced as discomfort) | Never | 0 | 0% | 1 | 50% |
| | Rarely | 0 | 0% | 0 | 0% |
| | Sometimes | 1 | 100% | 1 | 50% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Direct glare from the light fixtures beyond your immediate workspace (the light fixtures appear too bright) | Never | 0 | 0% | 1 | 50% |
| | Rarely | 0 | 0% | 0 | 0% |
| | Sometimes | 0 | 0% | 1 | 50% |
| | Often | 1 | 100% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Glare from your task lighting | Never | 0 | 0% | 1 | 50% |
| | Rarely | 1 | 100% | 0 | 0% |
| | Sometimes | 0 | 0% | 1 | 50% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| Direct glare from a window | Never | 0 | 0% | 1 | 50% |
| | Rarely | 0 | 0% | 0 | 0% |
| | Sometimes | 0 | 0% | 0 | 0% |
| | Often | 1 | 100% | 1 | 50% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| What is the | Very Warm | 0 | 0% | 1 | 50% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| color appearance of the lighting in your personal workspace? | Somewhat Warm | 1 | 100% | 0 | 0% |
| | Neutral | 0 | 0% | 1 | 50% |
| | Somewhat Cool | 0 | 0% | 0 | 0% |
| | Very Cool | 0 | 0% | 0 | 0% |
| | Don't Know | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| What would you prefer for the color appearance of the lighting in your personal workspace? | Very Warm | 0 | 0% | 0 | 0% |
| | Somewhat Warm | 0 | 0% | 1 | 50% |
| | Neutral | 0 | 0% | 1 | 50% |
| | Somewhat Cool | 1 | 100% | 0 | 0% |
| | Very Cool | 0 | 0% | 0 | 0% |
| | Don't Know | 0 | 0% | 0 | 0% |
| | Total | 1 | 100% | 2 | 100% |
| "Burning" or tired eyes after reading extensively | Never | 0 | 0% | This question not included in post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 0 | 0% | | |
| | About Once per Week | 1 | 100% | | |
| | Every Day | 0 | 0% | | |
| | Total | 1 | 100% | | |
| "Burning" or tired eyes after using computer extensively | Never | 0 | 0% | This question not included in post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 0 | 0% | | |
| | About Once per Week | 1 | 100% | | |
| | Every Day | 0 | 0% | | |
| | Total | 1 | 100% | | |
| I have to take a break to let my eyes recover | Never | 0 | 0% | This question not included in the post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 0 | 0% | | |
| | About Once per Week | 0 | 0% | | |
| | Every Day | 0 | 0% | | |
| | Total | 0 | 0% | | |
| Headache that you think is caused by your lighting | Never | 0 | 0% | This question not included in the post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 0 | 0% | | |
| | About Once per Week | 0 | 0% | | |
| | Every Day | 0 | 0% | | |
| | Total | 0 | 0% | | |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| If you could change the lighting in your office, what would you do? Please check all that apply. | Change the location of the overhead lighting fixtures relative to your workstation | 1 | 100% | 0 | 0% |
| | Make the overhead lighting fixtures produce more light | 0 | 0% | 0 | 0% |
| | Make the overhead lighting fixtures produce less light | 0 | 0% | 1 | 50% |
| | Make the overhead lighting fixtures less glary | 0 | 0% | 1 | 50% |
| | Change the aesthetic appearance of the lighting fixtures | 1 | 100% | 1 | 50% |
| | Change the color appearance of the light produced by the lighting fixtures | 0 | 0% | 0 | 0% |
| | Add a task light | 1 | 100% | 0 | 0% |
| | Be able to control the brightness/light output of the overhead lighting fixtures with a dimmer or high/low switch | 0 | 0% | 0 | 0% |
| | Get better access to a window view | 0 | 0% | 0 | 0% |
| | Get better acces to daylight | 1 | 100% | 0 | 0% |
| | Have lightbulbs replaced faster when they burn out and fixtures repaired faster when they break | 0 | 0% | 0 | 0% |
| | I would not change anything | 0 | 0% | 0 | 0% |

Building 602:

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Which of the following best describes the type of work you do? | People management, leadership, and/or training | 1 | 10% | 0 | 0% |
| | Computer aided design, engineering, or software development | 0 | 0% | 0 | 0% |
| | Combination of computer work, paper tasks, phone calls and meetings | 4 | 40% | 6 | 46% |
| | Facility Management | 0 | 0% | 0 | 0% |
| | Other | 5 | 50% | 7 | 54% |
| | Total | 10 | 100% | 13 | 100% |
| What is your age? | 30 or under | 3 | 30% | 2 | 15% |
| | 31-40 | 1 | 10% | 1 | 8% |
| | 41-50 | 3 | 30% | 4 | 31% |
| | over 50 | 3 | 30% | 6 | 46% |
| | Total | 10 | 100% | 13 | 100% |
| What is your gender? | female | 6 | 60% | 6 | 46% |
| | Male | 4 | 40% | 7 | 54% |
| | Total | 10 | 100% | 13 | 100% |
| Which of the following best describes your personal workspace? | Enclosed private office | 6 | 60% | 6 | 46% |
| | Cubicles with Partitions above standing eye level | 4 | 40% | 7 | 54% |
| | Cubicles with partitions below standing eye level | 0 | 0% | 0 | 0% |
| | Other | 0 | 0% | 0 | 0% |
| | Total | 10 | 100% | 13 | 100% |
| What type of computer screen do you have? | Laptop | 2 | 20% | 3 | 23% |
| | Flat Panel Screen | 6 | 60% | 8 | 62% |
| | Traditional Screen | 0 | 0% | 2 | 15% |
| | Other | 2 | 20% | 0 | 0% |
| | Total | 10 | 100% | 13 | 100% |
| On a typical day, how long are you in your personal workspace? | More than 6 hours | 3 | 30% | 1 | 8% |
| | 4-6 hours | 4 | 40% | 10 | 77% |
| | 2-4 hours | 3 | 30% | 2 | 15% |
| | Less than 2 hours | 0 | 0% | 0 | 0% |
| | Total | 10 | 100% | 13 | 100% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Are you able to see out a window while sitting in your workspace? | Yes | 1 | 10% | 3 | 23% |
| | No | 9 | 90% | 10 | 77% |
| | Total | 10 | 100% | 13 | 100% |
| If "Yes," do you like the view? | Yes | 0 | 0% | 0 | 0% |
| | No | 1 | 100% | 3 | 100% |
| | Total | 1 | 100% | 3 | 100% |
| Do you sit adjacent to a window? | Yes | 4 | 40% | 0 | 0% |
| | No | 6 | 60% | 3 | 100% |
| | Total | 10 | 100% | 3 | 100% |
| Which of the following most closely resembles the overhead lighting in your immediate work space (check all that apply)? | Picture 1 | 0 | 0% | 5 | 38% |
| | Picture 2 | 0 | 0% | 1 | 8% |
| | Picture 3 | 10 | 100% | 7 | 54% |
| | Other | 0 | 0% | 0 | 0% |
| | Total | 10 | 100% | 13 | 100% |
| Overall, is the lighting comfortable? | Yes | 4 | 40% | 6 | 46% |
| | No | 6 | 60% | 7 | 54% |
| | Total | 10 | 100% | 13 | 100% |
| Which of the following types of lighting fixtures most closely resembles the task lighting in your personal workspace? | Undercabinet Task light | 2 | 20% | 3 | 23% |
| | Destop Task light | 3 | 30% | 2 | 15% |
| | I do not have a task light | 5 | 50% | 8 | 62% |
| | Total | 10 | 100% | 13 | 100% |
| Which of the following most closely resembles the lighting on the walls in your general office | Uniformly bright walls | 5 | 50% | 7 | 54% |
| | Uneven light distribution on walls | 2 | 20% | 2 | 15% |
| | Accent Lighting on artwork only | 0 | 0% | 0 | 0% |
| | Walls are dim | 1 | 10% | 1 | 8% |
| | Other | 1 | 10% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| area? (check all that apply) | Do not know | 2 | 20% | 3 | 23% |
| | Total | 10 | 100% | 13 | 100% |
| Do the overhead lighting fixtures in your workspace turn on automatically (when you enter the space, on a set schedule, or both)? | Yes | 0 | 0% | 0 | 0% |
| | No | 10 | 100% | 13 | 100% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 10 | 100% | 13 | 100% |
| Do the overhead lighting fixtures in your workspace turn off automatically (when you leave the space, on a set schedule, or both)? | Yes | 0 | 0% | 4 | 31% |
| | No | 10 | 100% | 9 | 69% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 10 | 100% | 13 | 100% |
| If your lights turn off automatically, can you turn them back on from your immediate work area? | Yes | 0 | 0% | 3 | 75% |
| | No | 0 | 0% | 1 | 25% |
| | Do not know/ Does not apply | 8 | 100% | 0 | 0% |
| | Total | 8 | 100% | 4 | 100% |
| Can you control the overhead lights in your personal workspace without changing the lights in neighboring areas? | Yes | 6 | 60% | 5 | 38% |
| | No | 4 | 40% | 8 | 62% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 10 | 100% | 13 | 100% |
| How are your | Switch at wall | 10 | 100% | 13 | 100% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| overhead lights controlled (check all that apply)? | Handheld remote | 0 | 0% | 0 | 0% |
| | Interface at your computer | 0 | 0% | 0 | 0% |
| | Automated system/controlled by building management | 0 | 0% | 0 | 0% |
| | Other (Please specify) | 0 | 0% | 0 | 0% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 10 | 100% | 13 | 100% |
| To what extent can light levels from your overhead lights be adjusted? | Lights turn on and off only | 9 | 100% | 9 | 69% |
| | Light level settings are available for high, low, and/or medium | 0 | 0% | 2 | 15% |
| | Continuous dimming available | 0 | 0% | 2 | 15% |
| | Total | 9 | 100% | 13 | 100% |
| What type of control do you have for your task lighting? | On/Off switch | 6 | 67% | 5 | 38% |
| | Dimmer switch | 0 | 0% | 0 | 0% |
| | Other (please specify | 0 | 0% | 0 | 0% |
| | Does not apply | 3 | 33% | 8 | 62% |
| | Total | 9 | 100% | 13 | 100% |
| What type of shading system do you have to control the amount of daylight entering your windows? | Manual blinds (e.g., Venetian blinds) | 5 | 50% | 5 | 38% |
| | Manual windo shades(e.g.,roller shades) | 0 | 0% | 0 | 0% |
| | Automatic blinds or shades | 0 | 0% | 0 | 0% |
| | Other (please specify) | 1 | 10% | 1 | 8% |
| | No shading control | 0 | 0% | 3 | 23% |
| | I have no daylight in my workspace | 4 | 40% | 4 | 31% |
| | Total | 10 | 100% | 13 | 100% |
| Can you control the amount of daylight | Yes | 4 | 40% | 6 | 46% |
| | No | 2 | 20% | 0 | 0% |
| | Does not apply | 4 | 40% | 7 | 54% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| entering your windows without affecting other occupants? | Total | 10 | 100% | 13 | 100% |
| I am satisfied with my ability to control my overhead lighting. | Strongly Disagree | 6 | 60% | 3 | 23% |
| | Disagree | 4 | 40% | 4 | 31% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 0 | 0% | 4 | 31% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 2 | 15% |
| | Total | 10 | 100% | 13 | 100% |
| I am satisfied with my ability to control my task lighting. | Strongly Disagree | 1 | 10% | 1 | 8% |
| | Disagree | 2 | 20% | 0 | 0% |
| | Neutral | 2 | 20% | 0 | 0% |
| | Agree | 0 | 0% | 7 | 54% |
| | Strongly Agree | 2 | 20% | 1 | 8% |
| | Does not apply | 3 | 30% | 4 | 31% |
| | Total | 10 | 100% | 13 | 100% |
| I am satisfied with my ability to control my window shades or blinds. | Strongly disagree | 1 | 10% | 1 | 8% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 4 | 40% | 5 | 38% |
| | Strongly Agree | 2 | 20% | 1 | 8% |
| | Does not apply | 3 | 30% | 6 | 46% |
| | Total | 10 | 100% | 13 | 100% |
| My work surface is evenly lighted without very bright or dim spots. | Strongly Disagree | 1 | 13% | 0 | 0% |
| | Disagree | 5 | 63% | 4 | 33% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 1 | 13% | 7 | 58% |
| | Strongly Agree | 1 | 13% | 0 | 0% |
| | Does not apply | 0 | 0% | 1 | 8% |
| | Total | 8 | 100% | 12 | 100% |
| The lights flicker throughout the | Strongly Disagree | 3 | 38% | 1 | 8% |
| | Disagree | 3 | 38% | 5 | 42% |
| | Neutral | 2 | 25% | 4 | 33% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| day. | Agree | 0 | 0% | 1 | 8% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 1 | 8% |
| | Total | 8 | 100% | 12 | 100% |
| My skin is an unnatural tone under the lighting. | Strongly Disagree | 1 | 13% | 0 | 0% |
| | Disagree | 4 | 50% | 1 | 8% |
| | Neutral | 3 | 38% | 5 | 42% |
| | Agree | 0 | 0% | 4 | 33% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 2 | 17% |
| | Total | 8 | 100% | 12 | 100% |
| The lighting fixtures in the general office area around my workspace are nice-looking. | Strongly Disagree | 1 | 13% | 1 | 8% |
| | Disagree | 1 | 13% | 4 | 33% |
| | Neutral | 4 | 50% | 5 | 42% |
| | Agree | 2 | 25% | 2 | 17% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |
| The lighting helps create a good image for the organization. | Strongly Disagree | 2 | 25% | 2 | 17% |
| | Disagree | 1 | 13% | 3 | 25% |
| | Neutral | 3 | 38% | 5 | 42% |
| | Agree | 2 | 25% | 2 | 17% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |
| The room surfaces (walls, ceilings) have a pleasant brightness. | Strongly Disagree | 1 | 13% | 2 | 17% |
| | Disagree | 2 | 25% | 2 | 17% |
| | Neutral | 4 | 50% | 3 | 25% |
| | Agree | 1 | 13% | 5 | 42% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |
| Paper Tasks (reading and writing) | Much too Bright | 1 | 13% | 2 | 17% |
| | Too Bright | 3 | 38% | 2 | 17% |
| | Just Right | 2 | 25% | 5 | 42% |
| | Too Dim | 2 | 25% | 2 | 17% |
| | Much too Dim | 0 | 0% | 1 | 8% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Reading from a computer screen | Much too Bright | 2 | 25% | 2 | 17% |
| | Too Bright | 3 | 38% | 4 | 33% |
| | Just Right | 3 | 38% | 3 | 25% |
| | Too Dim | 0 | 0% | 3 | 25% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |
| Typing on keyboard | Much too Bright | 2 | 25% | 2 | 17% |
| | Too Bright | 2 | 25% | 1 | 8% |
| | Just Right | 3 | 38% | 6 | 50% |
| | Too Dim | 1 | 13% | 3 | 25% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |
| Filing or locating papers | Much too Bright | 1 | 13% | 2 | 17% |
| | Too Bright | 2 | 25% | 2 | 17% |
| | Just Right | 3 | 38% | 5 | 42% |
| | Too Dim | 2 | 25% | 3 | 25% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |
| Face to face conversations | Much too Bright | 1 | 13% | 2 | 17% |
| | Too Bright | 3 | 38% | 1 | 8% |
| | Just Right | 4 | 50% | 9 | 75% |
| | Too Dim | 0 | 0% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |
| Glare reflected from your work surface | Never | 1 | 13% | 2 | 17% |
| | Rarely | 2 | 25% | 5 | 42% |
| | Sometimes | 3 | 38% | 3 | 25% |
| | Often | 0 | 0% | 2 | 17% |
| | Always | 2 | 25% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |
| Glare from the light fixtures reflected on your computer screen | Never | 1 | 13% | 3 | 25% |
| | Rarely | 3 | 38% | 4 | 33% |
| | Sometimes | 1 | 13% | 3 | 25% |
| | Often | 0 | 0% | 2 | 17% |
| | Always | 3 | 38% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| | Total | 8 | 100% | 12 | 100% |
| Glare from the window reflected on your computer screen | Never | 2 | 29% | 6 | 55% |
| | Rarely | 2 | 29% | 3 | 27% |
| | Sometimes | 1 | 14% | 1 | 9% |
| | Often | 1 | 14% | 1 | 9% |
| | Always | 1 | 14% | 0 | 0% |
| | Total | 7 | 100% | 11 | 100% |
| Glare from the overhead lighting in your immediate workspace (usually experienced as discomfort) | Never | 1 | 13% | 2 | 17% |
| | Rarely | 2 | 25% | 5 | 42% |
| | Sometimes | 2 | 25% | 4 | 33% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 3 | 38% | 1 | 8% |
| | Total | 8 | 100% | 12 | 100% |
| Direct glare from the light fixtures beyond your immediate workspace (the light fixtures appear too bright) | Never | 5 | 63% | 2 | 17% |
| | Rarely | 1 | 13% | 5 | 42% |
| | Sometimes | 0 | 0% | 1 | 8% |
| | Often | 0 | 0% | 1 | 8% |
| | Always | 2 | 25% | 3 | 25% |
| | Total | 8 | 100% | 12 | 100% |
| Glare from your task lighting | Never | 5 | 63% | 6 | 55% |
| | Rarely | 1 | 13% | 2 | 18% |
| | Sometimes | 0 | 0% | 3 | 27% |
| | Often | 1 | 13% | 0 | 0% |
| | Always | 1 | 13% | 0 | 0% |
| | Total | 8 | 100% | 11 | 100% |
| Direct glare from a window | Never | 2 | 29% | 8 | 67% |
| | Rarely | 3 | 43% | 3 | 25% |
| | Sometimes | 1 | 14% | 0 | 0% |
| | Often | 0 | 0% | 1 | 8% |
| | Always | 1 | 14% | 0 | 0% |
| | Total | 7 | 100% | 12 | 100% |
| What is the color appearance of the lighting in | Very Warm | 1 | 13% | 2 | 17% |
| | Somewhat Warm | 0 | 0% | 3 | 25% |
| | Neutral | 3 | 38% | 3 | 25% |
| | Somewhat Cool | 1 | 13% | 2 | 17% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
| --- | --- | --- | --- | --- | --- |
| your personal workspace? | Very Cool | 1 | 13% | 1 | 8% |
| | Don't Know | 2 | 25% | 1 | 8% |
| | Total | 8 | 100% | 12 | 100% |
| What would you prefer for the color appearance of the lighting in your personal workspace? | Very Warm | 1 | 13% | 0 | 0% |
| | Somewhat Warm | 3 | 38% | 1 | 8% |
| | Neutral | 1 | 13% | 7 | 58% |
| | Somewhat Cool | 2 | 25% | 2 | 17% |
| | Very Cool | 0 | 0% | 2 | 17% |
| | Don't Know | 1 | 13% | 0 | 0% |
| | Total | 8 | 100% | 12 | 100% |
| "Burning" or tired eyes after reading extensively | Never | 1 | 13% | This question not included in post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 1 | 13% | | |
| | About Once per Week | 2 | 25% | | |
| | Every Day | 4 | 50% | | |
| | Total | 8 | 100% | | |
| "Burning" or tired eyes after using computer extensively | Never | 0 | 0% | This question not included in post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 1 | 13% | | |
| | About Once per Week | 2 | 25% | | |
| | Every Day | 5 | 63% | | |
| | Total | 8 | 100% | | |
| I have to take a break to let my eyes recover | Never | 0 | 0% | This question not included in the post-retrofit survey | |
| | Rarely | 1 | 13% | | |
| | About Once per Month | 1 | 13% | | |
| | About Once per Week | 4 | 50% | | |
| | Every Day | 2 | 25% | | |
| | Total | 8 | 100% | | |
| Headache that you think is caused by your lighting | Never | 1 | 13% | This question not included in the post-retrofit survey | |
| | Rarely | 4 | 50% | | |
| | About Once per Month | 2 | 25% | | |
| | About Once per Week | 0 | 0% | | |
| | Every Day | 1 | 13% | | |
| | Total | 8 | 100% | | |
| If you could change the lighting in your office, what would you do? | Change the location of the overhead lighting fixtures relative to your workstation | 2 | 25% | 5 | 42% |
| | Make the overhead lighting fixtures produce more light | 0 | 0% | 2 | 17% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Please check all that apply. | Make the overhead lighting fixtures produce less light | 5 | 63% | 5 | 42% |
| | Make the overhead lighting fixtures less glary | 3 | 38% | 5 | 42% |
| | Change the aesthetic appearance of the lighting fixtures | 1 | 13% | 4 | 33% |
| | Change the color appearance of the light produced by the lighting fixtures | 4 | 50% | 6 | 50% |
| | Add a task light | 3 | 38% | 1 | 8% |
| | Be able to control the brightness/light output of the overhead lighting fixtures with a dimmer or high/low switch | 8 | 100% | 7 | 58% |
| | Get better access to a window view | 5 | 63% | 5 | 42% |
| | Get better acces to daylight | 4 | 50% | 6 | 50% |
| | Have lightbulbs replaced faster when they burn out and fixtures repaired faster when they break | 2 | 25% | 1 | 8% |
| | I would not change anything | | 0% | 1 | 8% |

Building 988:

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Which of the following best describes the type of work you do? | People management, leadership, and/or training | 1 | 25% | 0 | 0% |
| | Computer aided design, engineering, or software development | 0 | 0% | 0 | 0% |
| | Combination of computer work, paper tasks, phone calls and meetings | 2 | 50% | 1 | 100% |
| | Facility Management | 0 | 0% | 0 | 0% |
| | Other | 1 | 25% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |
| What is your age? | 30 or under | 1 | 25% | 0 | 0% |
| | 31-40 | 0 | 0% | 0 | 0% |
| | 41-50 | 1 | 25% | 1 | 100% |
| | over 50 | 2 | 50% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |
| What is your gender? | female | 2 | 50% | 1 | 100% |
| | Male | 2 | 50% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |
| Which of the following best describes your personal workspace? | Enclosed private office | 3 | 75% | 0 | 0% |
| | Cubicles with Partitions above standing eye level | 1 | 25% | 0 | 0% |
| | Cubicles with partitions below standing eye level | 0 | 0% | 1 | 100% |
| | Other | 0 | 0% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |
| What type of computer screen do you have? | Laptop | 1 | 25% | 0 | 0% |
| | Flat Panel Screen | 2 | 50% | 1 | 100% |
| | Traditional Screen | 1 | 25% | 0 | 0% |
| | Other | 0 | 0% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |
| On a typical day, how long are you in your personal workspace? | More than 6 hours | 3 | 75% | 1 | 100% |
| | 4-6 hours | 1 | 25% | 0 | 0% |
| | 2-4 hours | 0 | 0% | 0 | 0% |
| | Less than 2 hours | 0 | 0% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Are you able to see out a window while sitting in your workspace? | Yes | 2 | 50% | 0 | 0% |
| | No | 2 | 50% | 1 | 100% |
| | Total | 4 | 100% | 1 | 100% |
| If "Yes," do you like the view? | Yes | 1 | 100% | 0 | N/A |
| | No | 2 | 200% | 0 | N/A |
| | Total | 1 | 100% | 0 | N/A |
| Do you sit adjacent to a window? | Yes | 1 | 25% | 0 | N/A |
| | No | 3 | 75% | 0 | N/A |
| | Total | 4 | 100% | 0 | N/A |
| Which of the following most closely resembles the overhead lighting in your immediate work space (check all that apply)? | Picture 1 | 0 | 0% | 0 | 0% |
| | Picture 2 | 3 | 75% | 0 | 0% |
| | Picture 3 | 0 | 0% | 1 | 100% |
| | Other | 0 | 0% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |
| Overall, is the lighting comfortable? | Yes | 2 | 50% | 1 | 100% |
| | No | 2 | 50% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |
| Which of the following types of lighting fixtures most closely resembles the task lighting in your personal workspace? | Undercabinet Task light | 0 | 0% | 1 | 100% |
| | Destop Task light | 1 | 25% | 0 | 0% |
| | I do not have a task light | 3 | 75% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |
| Which of the following most closely resembles the lighting on the walls in your general office | Uniformly bright walls | 1 | 25% | 1 | 100% |
| | Uneven light distribution on walls | 1 | 25% | 0 | 0% |
| | Accent Lighting on artwork only | 0 | 0% | 0 | 0% |
| | Walls are dim | 1 | 25% | 0 | 0% |
| | Other | 0 | 0% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| area? (check all that apply) | Do not know | 1 | 25% | 0 | 0% |
| | Total | 4 | 100% | 1 | 100% |
| Do the overhead lighting fixtures in your workspace turn on automatically (when you enter the space, on a set schedule, or both)? | Yes | 0 | 0% | 1 | 100% |
| | No | 3 | 100% | 0 | 0% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 3 | 100% | 1 | 100% |
| Do the overhead lighting fixtures in your workspace turn off automatically (when you leave the space, on a set schedule, or both)? | Yes | 0 | 0% | 0 | 0% |
| | No | 3 | 100% | 1 | 100% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 3 | 100% | 1 | 100% |
| If your lights turn off automatically, can you turn them back on from your immediate work area? | Yes | 0 | 0% | 0 | N/A |
| | No | 2 | 67% | 0 | N/A |
| | Do not know/ Does not apply | 1 | 33% | 0 | N/A |
| | Total | 3 | 100% | 0 | N/A |
| Can you control the overhead lights in your personal workspace without changing the lights in neighboring areas? | Yes | 2 | 67% | 0 | 0% |
| | No | 1 | 33% | 1 | 100% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 3 | 100% | 1 | 100% |
| How are your | Switch at wall | 3 | 100% | 1 | 100% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| overhead lights controlled (check all that apply)? | Handheld remote | 0 | 0% | 0 | 0% |
| | Interface at your computer | 0 | 0% | 0 | 0% |
| | Automated system/controlled by building management | 0 | 0% | 0 | 0% |
| | Other (Please specify) | 0 | 0% | 0 | 0% |
| | Do not know/ Does not apply | 0 | 0% | 0 | 0% |
| | Total | 3 | 100% | 1 | 100% |
| To what extent can light levels from your overhead lights be adjusted? | Lights turn on and off only | 2 | 67% | 1 | 100% |
| | Light level settings are available for high, low, and/or medium | 1 | 33% | 0 | 0% |
| | Continuous dimming available | 0 | 0% | 0 | 0% |
| | Total | 3 | 100% | 1 | 100% |
| What type of control do you have for your task lighting? | On/Off switch | 0 | 0% | 1 | 100% |
| | Dimmer switch | 0 | 0% | 0 | 0% |
| | Other (please specify | 0 | 0% | 0 | 0% |
| | Does not apply | 3 | 100% | 0 | 0% |
| | Total | 3 | 100% | 1 | 100% |
| What type of shading system do you have to control the amount of daylight entering your windows? | Manual blinds (e.g., Venetian blinds) | 1 | 50% | 0 | 0% |
| | Manual windo shades(e.g.,roller shades) | 0 | 0% | 0 | 0% |
| | Automatic blinds or shades | 0 | 0% | 0 | 0% |
| | Other (please specify) | 0 | 0% | 0 | 0% |
| | No shading control | 1 | 50% | 0 | 0% |
| | I have no daylight in my workspace | 0 | 0% | 1 | 100% |
| | Total | 2 | 100% | 1 | 100% |
| Can you control the amount of daylight | Yes | 1 | 50% | 0 | 0% |
| | No | 1 | 50% | 0 | 0% |
| | Does not apply | 0 | 0% | 1 | 100% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| entering your windows without affecting other occupants? | Total | 2 | 100% | 1 | 100% |
| I am satisfied with my ability to control my overhead lighting. | Strongly Disagree | 1 | 50% | 0 | 0% |
| | Disagree | 1 | 50% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 0 | 0% | 1 | 100% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| I am satisfied with my ability to control my task lighting. | Strongly Disagree | 1 | 50% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 0 | 0% | 0 | 0% |
| | Strongly Agree | 0 | 0% | 1 | 100% |
| | Does not apply | 1 | 50% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| I am satisfied with my ability to control my window shades or blinds. | Strongly disagree | 1 | 50% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 0 | 0% | 0 | 0% |
| | Strongly Agree | 1 | 50% | 0 | 0% |
| | Does not apply | 0 | 0% | 1 | 100% |
| | Total | 2 | 100% | 1 | 100% |
| My work surface is evenly lighted without very bright or dim spots. | Strongly Disagree | 1 | 50% | 0 | 0% |
| | Disagree | 1 | 50% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 0 | 0% | 1 | 100% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| The lights flicker throughout the | Strongly Disagree | 1 | 50% | 1 | 100% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| day. | Agree | 1 | 50% | 0 | 0% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| My skin is an unnatural tone under the lighting. | Strongly Disagree | 1 | 50% | 0 | 0% |
| | Disagree | 1 | 50% | 1 | 100% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 0 | 0% | 0 | 0% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| The lighting fixtures in the general office area around my workspace are nice-looking. | Strongly Disagree | 1 | 50% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 0 | 0% | 1 | 100% |
| | Agree | 1 | 50% | 0 | 0% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| The lighting helps create a good image for the organization. | Strongly Disagree | 1 | 50% | 0 | 0% |
| | Disagree | 0 | 0% | 0 | 0% |
| | Neutral | 1 | 50% | 0 | 0% |
| | Agree | 0 | 0% | 1 | 100% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| The room surfaces (walls, ceilings) have a pleasant brightness. | Strongly Disagree | 1 | 50% | 0 | 0% |
| | Disagree | 1 | 50% | 0 | 0% |
| | Neutral | 0 | 0% | 0 | 0% |
| | Agree | 0 | 0% | 1 | 100% |
| | Strongly Agree | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Paper Tasks (reading and writing) | Much too Bright | 0 | 0% | 0 | 0% |
| | Too Bright | 0 | 0% | 0 | 0% |
| | Just Right | 0 | 0% | 1 | 100% |
| | Too Dim | 2 | 100% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Reading from a computer screen | Much too Bright | 0 | 0% | 0 | 0% |
| | Too Bright | 0 | 0% | 0 | 0% |
| | Just Right | 0 | 0% | 1 | 100% |
| | Too Dim | 2 | 100% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Typing on keyboard | Much too Bright | 0 | 0% | 0 | 0% |
| | Too Bright | 0 | 0% | 0 | 0% |
| | Just Right | 1 | 50% | 1 | 100% |
| | Too Dim | 1 | 50% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Filing or locating papers | Much too Bright | 0 | 0% | 0 | 0% |
| | Too Bright | 0 | 0% | 0 | 0% |
| | Just Right | 1 | 50% | 1 | 100% |
| | Too Dim | 1 | 50% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Face to face conversations | Much too Bright | 0 | 0% | 0 | 0% |
| | Too Bright | 0 | 0% | 0 | 0% |
| | Just Right | 1 | 50% | 1 | 100% |
| | Too Dim | 1 | 50% | 0 | 0% |
| | Much too Dim | 0 | 0% | 0 | 0% |
| | Does not apply | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Glare reflected from your work surface | Never | 1 | 50% | 0 | 0% |
| | Rarely | 0 | 0% | 1 | 100% |
| | Sometimes | 0 | 0% | 0 | 0% |
| | Often | 1 | 50% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Glare from the light fixtures reflected on your computer screen | Never | 1 | 50% | 0 | 0% |
| | Rarely | 0 | 0% | 0 | 0% |
| | Sometimes | 0 | 0% | 1 | 100% |
| | Often | 1 | 50% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| | Total | 2 | 100% | 1 | 100% |
| Glare from the window reflected on your computer screen | Never | 1 | 50% | 1 | 100% |
| | Rarely | 1 | 50% | 0 | 0% |
| | Sometimes | 0 | 0% | 0 | 0% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Glare from the overhead lighting in your immediate workspace (usually experienced as discomfort) | Never | 1 | 50% | 0 | 0% |
| | Rarely | 0 | 0% | 0 | 0% |
| | Sometimes | 0 | 0% | 1 | 100% |
| | Often | 1 | 50% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Direct glare from the light fixtures beyond your immediate workspace (the light fixtures appear too bright) | Never | 2 | 100% | 0 | 0% |
| | Rarely | 0 | 0% | 0 | 0% |
| | Sometimes | 0 | 0% | 1 | 100% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Glare from your task lighting | Never | 2 | 100% | 1 | 100% |
| | Rarely | 0 | 0% | 0 | 0% |
| | Sometimes | 0 | 0% | 0 | 0% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| Direct glare from a window | Never | 1 | 50% | 1 | 100% |
| | Rarely | 1 | 50% | 0 | 0% |
| | Sometimes | 0 | 0% | 0 | 0% |
| | Often | 0 | 0% | 0 | 0% |
| | Always | 0 | 0% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| What is the color appearance of the lighting in | Very Warm | 0 | 0% | 0 | 0% |
| | Somewhat Warm | 0 | 0% | 1 | 100% |
| | Neutral | 1 | 50% | 0 | 0% |
| | Somewhat Cool | 0 | 0% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| your personal workspace? | Very Cool | 0 | 0% | 0 | 0% |
| | Don't Know | 1 | 50% | 0 | 0% |
| | Total | 2 | 100% | 1 | 100% |
| What would you prefer for the color appearance of the lighting in your personal workspace? | Very Warm | 0 | 0% | 0 | 0% |
| | Somewhat Warm | 0 | 0% | 0 | 0% |
| | Neutral | 1 | 50% | 0 | 0% |
| | Somewhat Cool | 0 | 0% | 0 | 0% |
| | Very Cool | 0 | 0% | 0 | 0% |
| | Don't Know | 1 | 50% | 1 | 100% |
| | Total | 2 | 100% | 1 | 100% |
| "Burning" or tired eyes after reading extensively | Never | 0 | 0% | This question not included in post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 0 | 0% | | |
| | About Once per Week | 0 | 0% | | |
| | Every Day | 2 | 100% | | |
| | Total | 2 | 100% | | |
| "Burning" or tired eyes after using computer extensively | Never | 0 | 0% | This question not included in post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 0 | 0% | | |
| | About Once per Week | 0 | 0% | | |
| | Every Day | 2 | 100% | | |
| | Total | 2 | 100% | | |
| I have to take a break to let my eyes recover | Never | 0 | 0% | This question not included in the post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 0 | 0% | | |
| | About Once per Week | 0 | 0% | | |
| | Every Day | 2 | 100% | | |
| | Total | 2 | 100% | | |
| Headache that you think is caused by your lighting | Never | 0 | 0% | This question not included in the post-retrofit survey | |
| | Rarely | 0 | 0% | | |
| | About Once per Month | 0 | 0% | | |
| | About Once per Week | 1 | 50% | | |
| | Every Day | 1 | 50% | | |
| | Total | 2 | 100% | | |
| If you could change the lighting in your office, what would you do? | Change the location of the overhead lighting fixtures relative to your workstation | 1 | 50% | 0 | 0% |
| | Make the overhead lighting fixtures produce more light | 1 | 50% | 0 | 0% |

| Questions | Answers | # of Pre-retrofit respondents | % of Pre-retrofit respondents | # of Post-retrofit respondents | % of Post-retrofit respondents |
|---|---|---|---|---|---|
| Please check all that apply. | Make the overhead lighting fixtures produce less light | 0 | 0% | 1 | 100% |
| | Make the overhead lighting fixtures less glary | 0 | 0% | 1 | 100% |
| | Change the aesthetic appearance of the lighting fixtures | 0 | 0% | 0 | 0% |
| | Change the color appearance of the light produced by the lighting fixtures | 0 | 0% | 0 | 0% |
| | Add a task light | 1 | 50% | 0 | 0% |
| | Be able to control the brightness/light output of the overhead lighting fixtures with a dimmer or high/low switch | 2 | 100% | 0 | 0% |
| | Get better access to a window view | 0 | 0% | 0 | 0% |
| | Get better acces to daylight | 0 | 0% | 1 | 100% |
| | Have lightbulbs replaced faster when they burn out and fixtures repaired faster when they break | 0 | 0% | 0 | 0% |
| | I would not change anything | 0 | 0% | 0 | 0% |

# Appendix I: Equipment Calibration and Quality Assurance Sampling

## Calibration of Equipment

The power metering equipment and light meters used in power and illuminance characterization respectively are highly sophisticated. This equipment is pre-calibrated and does not need on-site calibration.

## Quality Assurance Sampling

Current measurements from CTs were checked against handheld ammeters when installed and will be checked again when removed. Between these checks, all data files were screened for drift based on the following criteria:

a. Do current readings drop below -0.1A at any time?
b. Do current readings when all lights associated with the circuit appear to be turned off shift consistently by >0.1A in either direction over the course of pre-retrofit or post-retrofit data collection?

An assessment of the minimum current recorded each day revealed that current readings never dropped below -0.1A on any of the metered circuits, except during temporary power outages (data collected during power outages was excluded from analysis).

Nighttime shift was evaluated by comparing the first 5 daily minimum current readings when all the lights appeared to be off with the last 5 daily minimum readings with the same conditions, both pre-retrofit and post-retrofit. Readings when all the lights are turned off are not expected to stay the same between the pre-retrofit and post-retrofit periods due to the additional standby power associated with some of the control equipment in the post-retrofit system. From this assessment, 2 out of 16 pre-retrofit circuits and 3 out of 16 post-retrofit circuits merited further scrutiny. These were:

- Nighttime minimum readings when all the lights are expected to be off in building 602, circuit 20, exhibited a shift of -0.138A between the first 5 days and the last 5 days of the pre-retrofit study period. This downward trend stabilizes to well within the 0.1A CT tolerance by 23 days into the pre-retrofit study period, and readings on the circuit were stable within the 0.1A range during the post-retrofit period. An upper bound estimate of the error from this possible CT drift during 23 out of 71 study days is approximately 5% of calculated annual energy use on the circuit, and a much lower percentage of building energy use. Due to the lack of information about what caused the nighttime drift in the early dataset, data were not adjusted based on this trend.

- The pre-retrofit dataset of circuit 16 in building 988 showed that the lowest current levels early in the metering period were lower than current levels at the end. However, the data clearly show several typical nighttime current levels, which are assumed to be associated with different groups of lights left on overnight, and these do not exhibit drift during the study period. In particular, a few days more than halfway into the study period

had the same nighttime current readings as the days at the beginning of the metering period. Differences can therefore be attributed to different combinations of lights being left on overnight rather than to inaccurate CT readings.

- All three metered circuits in building 279 during the post-retrofit period exhibited wide daily variation in nighttime power levels. This behavior is believed to be due to varying control system standby power over the course of the study period. Some occupants sometimes manually switched the lights off, which shuts off the power to the ballast controller circuits, reducing the standby load on the circuit. On the other hand, when the control system turns the lights off automatically the ballast controller circuit stays energized.

Based on this assessment, all CT readings included in the analysis were assumed to be correct within the CT margin of error of 0.1A. No adjustments were made to CT readings prior to analysis except that negative readings were corrected to zero.